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Task switching and short-term retention: The role of memory load in task switching performance

by

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ABSTRACT

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Shifting, which is the process of switching task sets between two or more tasks, incurs a cost: participants are slower and more error prone when a switch is required, relative to when the same task is performed in a sequential manner. Recent research in our lab has found a performance dissociation between two task switching paradigms in ML, a patient with reduced short-term memory (STM) capacity. The present study investigates the hypothesis that this dissociation is a result of memory load differences between the two shifting paradigms. We tested this hypothesis by measuring shifting abilities in patients with phonological and semantic short-term memory deficits, as well as age-matched controls under standard and articulatory suppression conditions. The results suggest that task-related memory demands impair the shifting performance of patients with STM deficits, and that phonological (but not semantic) retention contributes to shifting as task requirements increase.

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Executive control processes are essential to our ability to perform flexibly and adaptively in everyday life. Few models describing the mechanisms underlying executive control have been as influential as Baddeley's multi-component model of working memory that includes a central executive component (WM; Baddeley, 1986, 2003; Baddeley & Hitch, 1974). Critically, this model proposes peripheral storage systems that are separate from a system for executive (or cognitive) control. While the storage systems, such as the phonological loop, are well-understood, the central executive is not (Baddeley, 2003). Even so, the central executive is thought to play a central role in complex cognition. Multiple lines of research have suggested that this cognitive control mechanism can be fractionated and better understood by specifying more specific processes (e.g. Baddeley, 1996, 2003; Miyake et al., 2000). One such executive control component is shifting, which involves the ability to change task sets, an ability that is critical for cognitive flexibility (e.g. Miyake et al., 2000; Rogers & Monsell, 1995).

The present study focuses on this shifting component of executive function, which involves switching between two (or more) separate tasks. In task switching paradigms, participants typically perform two tasks, either in single (pure) task blocks or multiple (mixed) task blocks. In pure blocks, participants perform the same task throughout the entire block; in mixed blocks, participants alternate between task 1 and task 2 in a predictable manner and/or as per cues specifying which task to perform. Additionally, mixed blocks can be composed of a variety of task alternations – switches can occur on every trial (e.g. Jersild, 1927), or after alternating runs of a single task (e.g. $task_1$, $task_1$, $task_2$, $task_2$, $task_1$, $task_{1, \ldots}$). In this later alternating runs design, mixed blocks contain both task-switch and task-repeat trials (e.g. Rogers & Monsell, 1995).

While switching is seemingly a simple process, there is a switch cost: participants are slower and more error prone on switch trials, relative to trials in which the same task is performed consecutively (e.g. Jersild, 1927; Rogers & Monsell, 1995; Spector & Biederman, 1976). Recent research, has distinguished between two types of switch costs: global switch costs and local switch costs (Kray & Lindenberger, 2000; Mayr, 2001; Mayr & Liebscher, 2001). Global switch costs are measured as the difference between mixed blocks and the average of the pure blocks. Specifically, global costs are only present when two different tasks must be performed on the same set of stimuli. For example, costs were incurred with the requirement to alternate between adding or subtracting 3 from a list of numbers, or with the requirement to alternate between producing antonyms or verbs to a list of words, relative to pure task blocks. In contrast, no global switch costs were found when the stimuli themselves unambiguously indicated which task should be performed on a given trial, such as when subjects alternated between subtracting 3 from a number and producing antonyms to printed words (e.g. Jersild, 1927; Spector & Biederman, 1976). This global switch cost is hypothesized to represent the costs associated with updating, manipulating, and maintaining multiple task sets in working memory during the mixed blocks (Kray & Lindenberger, 2000; Mayr, 2001), as multiple task sets need to be available in mixed blocks, whereas only a single task set needs to be available in pure blocks (Rogers & Monsell, 1995). According to

Mayr (2001), global costs reflect an updating process that refreshes task sets in mixed blocks.

The local switch cost is measured as the performance difference between switch and repeat trials within the mixed block (Rogers & Monsell, 1995). For example, participants might alternate between four trials of one task and four trials of another task (e.g. $\underline{task_1}$, $task_1$, $\underline{task_2}$, $task_2$, $\underline{task_1}$, …) – local switch costs would be computed by subtracting the mean response times on repeat trials (not underlined) from the mean response time on switch trials (underlined). This switch cost is hypothesized to reflect the processes involved in initiating and executing task set shifts, with some researchers hypothesizing that a major component of this cost is the need to retrieve upcoming task sets from long-term memory (Mayr & Kliegl, 2000b). Many have suggesting this local switch cost is a purer measure of the actual switching between tasks (Kray & Lindenberger, 2000; Mayr, 2001; Rogers & Monsell, 1995).

Support for the distinction between global and local switch costs comes from studies of aging, with aging effects being found in global but not local switch costs (e.g. Kray & Linderberger, 2000, Mayr, 2001; Mayr & Liebscher, 2001; cf Mayr & Kliegl, 2000a). Kray and Linderberger (2000), for example, used a predictable but implicitly cued switching paradigm to investigate age differences in global and local switch costs. Age differences were found in global switch costs, such that middle-aged (*M* age = 50.3) and older (*M* age = 69.5) adults showed greater global switch costs than young adults (*M* age = 29.6). In contrast, age effects were either minimal or not observed in local switch costs. Mayr (2001) also found similar results in an unpredictable, explicitly cued shifting paradigm, when the same response keys were used for both tasks. Kray and Linderberger concluded that these results suggest middle-aged and older adults are "specifically impaired in working memory abilities such as keeping task instructions online and keeping track of the task sequence while switching between tasks", relative to young adults (p. 136). Further supporting the separation of global and local switching processes as distinct executive processes, Kray and Linderberger found that these switch costs are better represented by confirmatory factor analysis with two latent factors, as opposed to a single-factor model.

Global and local switch costs are both reduced when participants are given cues and time to prepare for the upcoming task. Cues, which specify the task to be performed on the upcoming trial, provide foreknowledge about the upcoming task. Increasing the preparatory interval, or the time between cue and target onset, allows for longer cue processing, and therefore reduced switch costs. Several researchers have proposed that this preparation interval allows for the activation of the relevant task set for the upcoming trial. That is, the cue and preparation interval provide an participants with the opportunity to endogenously reconfigure their task set (e.g. Meiran, Gotler & Perlman, 2001; Rogers & Monsell, 1995). Interestingly, however, switch costs are not eliminated, and there is generally no preparation benefit beyond a ~600 millisecond (ms) cue-stimulus interval (CSI) (e.g. Allport, Styles & Hsieh, 1994; Rogers & Monsell, 1995). This suggests that participants receive no additional preparation benefit beyond half a second (at least when both tasks are matched to the same response buttons). The fact that switch costs can be reduced at this point, but not eliminated, suggests that some task set reconfiguration cannot be completed until some target processing has occurred (e.g. Allport et al., 1994; Mayr & Keele, 2000; Meiran, 1996; Rogers & Monsell, 1995).

Previous research in our lab has investigated shifting in aphasic patients with short-term memory (STM) deficits. Interestingly, patient ML, with both semantic and phonological STM deficits, showed a large performance dissociation between two different switching tasks. One task involved switching between judging the small (i.e., local) or large (i.e., global) figure in a Navon figures task, depending on the color of the stimulus. If the stimulus was blue, ML was instructed to judge the number of lines in the small, local figure; if black, ML was instructed to judge the number of lines in the large, global figure. Despite fine performance in pure blocks, patient ML unexpectedly found switching in the mixed blocks virtually impossible. In contrast, ML was unimpaired in a cued shifting task involving judgments of shape or color, as he produced only small switch costs (that were not significantly different from controls) and minimal errors. In this cued shifting task, each trial contained a verbal cue (e.g. "Shape") indicating which target dimension to respond to.

Why did ML's performance differ between these two tasks? We hypothesized that his difficulty with the Navon figures switching task resulted from the memory demands of the task itself. Each trial required the interpretation of the implicit color cue to determine which task to perform on a given trial. Additionally, cue processing was followed by target processing which consisted of determining the number of lines in the target figure, requiring that he remember a rule to determine the correct response, as opposed to responding to an obvious stimulus attribute. Thus, this switching task was actually quite demanding. In contrast, the cued shifting task reduced the memory load by minimizing the need to process an implicit cue on each trial. Additionally, responses in this task were made to obvious stimulus attributes (target shape or color), requiring minimal demands for remembering the rule that determines the response. The present research further investigates the role of memory load (as a function of cue processing requirements) on shifting in patients with STM deficits to determine the type of STM that might be involved. Prior work in our lab has provided evidence that aphasic patients may have either phonological or semantic STM deficits (Martin & He, 2004; Martin & Romani, 1994; Martin, Shelton, & Yaffee, 1994). As ML has a deficit in both, it is possible that either might contribute to his difficulty with switching in the Navon figures task.

Several lines of research with healthy subjects have provided evidence for the idea that task switching utilizes phonological STM. For example, researchers have argued that the phonological loop (or related language processes) is critical for efficient task switching (e.g. Baddeley, Chincotta & Adlam, 2001; Bryck & Mayr, 2005; Emerson & Miyake, 2003; Hester & Garavan, 2005; Mecklinger, von Cramon, Springer, and Matthes-von Cramon, 1999; Miyake, Emerson, Padilla & Ahn, 2004; Saeki & Saito, 2004b, 2009; Spector & Biederman, 1976). Baddeley et al. (2001) and others (e.g. Emerson & Miyake, 2003; Spector & Biederman, 1976) have found cueing effects on global switch costs. Cued shifting, in which an explicit cue indicated which task to perform on the upcoming trial, resulted in significantly smaller switch costs than uncued shifting, where participants were required to track the task to be performed on each trial themselves. Additionally, Baddeley and colleagues found that articulatory suppression differentially affected cued and uncued switching, such that suppression did not increase switch costs on cued trials, though it did significantly increase switch costs in uncued trials. The interaction between cueing effects and articulatory suppression suggests that global switching processes rely on phonological STM processes for maintaining the currently relevant task set, when explicit cues are not provided. Thus, previous research has suggested a critical role for phonological retention in maintaining the current task set when task sets must be self-cued.

In contrast to global switch costs, previous research has found discrepant effects of articulatory suppression on local switch costs. Miyake and colleagues (2004) found different effects of articulatory suppression on local switch costs, depending on the type of cue used in a randomly cued shifting paradigm. When each trial was explicitly cued with words that indicated the task to be performed, articulatory suppression had minimal, nonsignificant effects on switch costs. In contrast, on trials explicitly cued by a letter ('C' for the color task, 'S' for the shape task), articulatory suppression significantly increased local switch costs. Miyake et al. suggested that explicit word cues are directly translated into task sets; in contrast, less explicit cues (such as letters) require an additional cue-translation process to transform the symbolic cue into an informative task set name (e.g. translating the "C" cue into the task set name "Color"). These translated, informative cue names are then used as a retrieval aid for task goals on switch (but not repeat) trials when task sets are not automatically activated. This cue-translation process would only be necessary on switch trials, as cue repetition on repeat trials would allow participants to use the currently activated task set. Further support for a role of language processes in measures of local switching comes from a study in patients with brain damage. Mecklinger and colleagues (1999) used an implicitly cued shifting paradigm in which patients performed object or spatial visual discrimination tasks. The authors found higher local switch costs in patients with left hemisphere brain damage, relative to patients with right hemisphere brain damage. Critically, this effect in left hemisphere patients was driven by larger costs in a sub-group of left hemisphere patients with language and speech disorders. The authors suggest effective local shifting in this implicitly cued shifting task involves the initiation of task set reconfiguration, utilizing a verbal representation of the upcoming task. They concluded that their language disordered left hemisphere patients were impaired in generating this verbal representation, thus resulting in longer reaction times on switch relative to repeat trials. In summary, the Miyake and Mecklinger studies have both proposed an important role for cue translation processes on switch but not repeat trials.

A more recent study by Saeki and Saito (2009) questioned the assumption that increases in local switch costs were caused by cue-translation on switch trials (as claimed by Miyake et al., 2004). Saeki and Saito used different cue types in investigating local switch costs. They found no effect of articulatory suppression with traditional cues, i.e. when cues that indicated which task should be performed on a given trial (task cues). In contrast, articulatory suppression negatively affected local switch costs when transition cues were used – that is, when cues only indicated whether a given task set should be repeated or switched, relative to the previous trial. As cue translation was required for both task cue and transition cue conditions in this study, Saeki and Saito rule out the possibility that suppression disrupts cue decoding (as proposed by Miyake et al., 2004). Instead, Saeki and Saito suggest that articulatory suppression disrupts task set name retrieval (which is likely in verbal format), when cues are not transparent.

Other studies have suggested that phonological processes are equally involved in both switch and repeat trials, such that articulatory suppression does not result in increased local switch costs. Bryck and Mayr (2005), for example, failed to replicate Miyake and colleagues' suppression effects in local switch costs, and along with Saeki and Saito (2004b), found that suppression had similar slowing effects on both switch and repeat trials, resulting in no change in local switch costs as a function of suppression (even in the presence of external task cues). As a result, Bryck and Mayr suggested that phonological information contributes to the maintenance of the current task sequence, which is necessary on both switch and repeat trials. This suggestion is in line with Emerson and Miyake (2003), who proposed that phonological processes function as an internal cueing device in global shifting (p. 153).

Thus, phonological processes have been hypothesized to play a similar role in both global and local switch cost measures, though the findings for local switch costs are mixed. That is, phonological processes are thought to enable participants to keep track of the relevant task set, serving as a self-cueing device when a task cues are not explicitly provided. However, phonological disruption may differentially affect global and local shifting measures. That is, if self-cueing occurs on both switch and repeat trials, phonological disruption does result in increased local switch costs. In contrast, it does result in increased global switch costs, relative to standard (i.e. non-articulatory suppression) conditions.

To summarize, previous research has hypothesized a relationship between switching costs and phonological STM rehearsal and/or retention. These findings are consistent with our hypothesis that impaired performance for patient ML on the Navon figures task switching paradigm is due to increased WM load and lead to the general prediction that deficits in phonological STM should be related to difficulties in task switching with implicit cues. The present study investigated this hypothesis explicitly by manipulating the cue type across experiments, such that cue processing requirements served as a WM load manipulation. As we have seen, several studies have shown that the cue type greatly affects global switch costs, though the effects on local costs are less clear. Across both switch costs, however, it has been hypothesized that phonological processes may be used in shifting-related processes such as task maintenance and task retrieval (e.g. Baddeley et al., 2001; Emerson & Miyake, 2003; Miyake et al., 2004). Thus, the present study investigated and compared three cueing conditions: a) full cueing, b) partial cueing, and c) full symbolic cueing in patients with short-term memory deficits and age-matched controls. In the full cueing condition, a word cue ('Color', 'Shape') was presented throughout the duration of the trial (until a response was made). The partial cueing condition presented the cue only during the preparation interval (but not during the target presentation). Lastly, the full symbolic cueing condition used symbols (instead of words) as cues for each task. In light of previous research, we predict increased switch costs in conditions requiring more active short-term maintenance for both patients and age-matched controls, and exaggerated switch cost load effects in patients with short-term memory deficits, particularly in those conditions making the greatest STM demands.

While the literature on switching from healthy suggests an important role of phonological retention in switching, it is possible that semantic retention also plays a role. It is unclear whether patient ML's difficulties with the Navon figures switching task were specifically related to his phonological STM deficits, as patient ML has both phonological and semantic STM deficits. Thus, another goal of the present study is to investigate the relationship between shifting and both phonological and semantic retention. That is, are switch costs differentially related to either phonological or semantic short-term retention, and do these relationships differ by cue type/working memory load? Recent research has suggested that semantic STM deficits in aphasia result from a disruption to a domain-general semantic control system, the operation of which is reflected in performance on complex tests of executive function (Hoffman, Jefferies, Ehsan, Hopper & Lambon Ralph, 2009). These findings suggest that semantic STM deficits result from deficits in executive control. However, Hoffman et al. have done little to specify whether these semantic STM deficits result from deficits to specific executive functions, such as a specific deficit in inhibition as proposed by Hamilton and Martin (2005, 2007). Additionally, Allen, R. Martin and N. Martin (in preparation) have provided evidence suggesting that the relationship between executive function and STM deficits might be better interpreted in light of phonological retention abilities, with deficits in phonological STM causing deficits on executive function tasks that have a verbal component (e.g. Wisconsin Card Sorting Task (WCST), e.g. Baldo et al., 2005; Dunbar & Sussman, 1995; Letho, 1996). Specifically, executive task performance was significantly correlated with various measures of phonological retention in nineteen aphasic patients with short-term memory deficits for tasks with a verbal component (e.g., WCST) but not for a task drawing primarily on visual and spatial abilities (Tower of Hanoi). This corroborates previous research suggesting a role for short-term retention and language processes in executive task performance for complex tasks with a verbal component (e.g. Baldo et al., 2005; Dunbar & Sussman, 1995; Letho, 1996). Thus, interest in the executive function abilities of aphasic patients has implications both for theories of STM deficits and theories of executive control.

As mentioned, the present research examined the relation between STM deficits (both phonological and semantic, as measured by the rhyme and category probe) and the shifting component of executive function (Miyake et al., 2000) to determine whether shifting ability is differentially related to phonological or semantic retention, and whether this relationship is moderated by the memory load of the task itself. In controls (with the exception of Experiment 1), this question was examined in an exploratory fashion by looking at the correlation between global and local switch costs and phonological and semantic retention, as measured by the rhyme and category probe tasks (Martin et al., 1994; Martin & He, 2004). In both the rhyme and category probe tasks, participants hear a list of words, followed by a probe word. In the rhyme probe task, participants indicate whether the probe word rhymes with any of the previous words. In the category probe task, participants indicate whether the probe word is in the same category as any of the previous words. Given previous research on healthy individuals suggesting a role for phonological STM processes in shifting measures that require task set maintenance, we expected to find a relationship between phonological retention and high WM load switching measures. More specifically, we predicted a correlation between rhyme probe performance and global switching abilities in the symbolic cueing condition – the condition in which subjects must either process symbolic cues or use self-cueing to maintain the relevant task set. Additionally, finding that the relationship between switch costs and phonological retention depends on memory load would further support the notion that poor performance on global executive function tasks result from deficits in phonological retention (Allen & Martin, 2009; Allen, Martin & Martin, in prep; see also: Baldo et al., 2005; Dunbar & Sussman, 1995; Letho, 1996).

As previously mentioned, the present study manipulated cue processing requirements to investigate the role of phonological processes in global and local switch costs. Experiment 1 was a pilot experiment used to ensure that a multiple patients with STM deficits were able to perform the cued shifting paradigm used in Experiments 2-4. Experiment 2 served as a low load baseline for Experiments 3 and 4, which manipulated the shifting task's WM by varying cue processing requirements. In healthy older adults, we also investigated changes in switch costs as a function of phonological disruption (i.e. articulatory suppression). Lastly, the relationship between shifting measures and phonological and semantic retention was investigated in an exploratory fashion.

Patient Background

This section provides patient background information for all of the patients tested in the four experiments discussed below. All patients are stoke aphasics, at least 3 years post-stroke. Not all patients were available for each experiment (Table 1).

Patient BB. Patient BB is a 49-year-old right-handed male with a left-hemisphere lesion incurred from a cerebrovascular accident (CVA) in 2000. He received his doctorate degree in Computer Science. Prior to his stroke, he was employed as a Computer Science professor. BB has an extensive lesion, including his left frontal, parietal and superior temporal lobes. In addition, he has some insular and subcortical damage. BB's speech is non-fluent, including both pauses and word-finding difficulties.

Patient BQ. Patient BQ is a 67-year-old right-handed male with a left-hemisphere lesion incurred from a CVA in 2000. He completed 16 years of school, and was a business owner and engineer prior to his stroke. BQ has an extensive left hemisphere temporal-parietal lesion that includes the superior temporal gyrus, and a large majority of the parietal lobe. His lesion also extends into posterior regions of the frontal lobe, including BA 44. Some insular damage is also present. BQ's speech is extremely non-fluent, including long pauses and word-finding difficulties.

Patient ER. Patient ER is a 58-year-old right-handed female with a left-hemisphere lesion incurred from a CVA in 2001. She completed 17 years of school, and was a homemaker prior to her stroke. ER's lesion is restricted to the left parietal lobe, sparing the angular gyrus. ER's speech is non-fluent, including both pauses and word-finding difficulties.

Patient EV. Patient EV is a 53-year-old right-handed female with a left-hemisphere lesion incurred from a CVA in 2000. She completed 16 years of school, receiving her bachelor's degree in Accounting and was employed as a bank manager prior to her stroke. EV has a left frontal lobe lesion, including BA 44 and 45, with slight extension into the middle frontal gyrus. Some insular damage is also present. EV's speech is relatively fluent, with some word-finding difficulties.

Patient MB. Patient MB is a 60-year-old right-handed male with a left-hemisphere lesion incurred from a CVA in 2004. He completed 13 years of school, and was employed as consultant/business owner both prior to and on and off several years following his stroke. MB's has a left parietal lobe lesion, with small subcortical infarcts of the posterior and lateral right parietal lobe. MB's speech is relatively fluent, with a tendency for phonological errors, especially with increases in word length.

Patient NC. Patient NC is a right-handed male with a left-hemisphere lesion incurred from a CVA in 2001. He received his bachelors in Business, and was employed as the owner of a temp agency prior to his stroke. NC's lesion information was not available. His speech is slightly non-fluent.

Patient ML. Patient ML is a 68-year-old right-handed male with a left-hemisphere lesion incurred from a CVA in 1990. He completed two years of college coursework, and was employed as a draftsman prior to his stroke. His lesion encompasses the left inferior and middle frontal gyri and large lateral areas of the superior and inferior left parietal lobe, though with some sparing of the supramarginal gyrus and angular gyrus (Biegler, Crowther, & Martin, 2008). ML's speech is non-fluent, including both pauses and word-finding difficulties.

Patient SH. Patient SH is an 81-year-old right-handed male with a left-hemisphere lesion incurred from a CVA in 2005. He completed 11 years of schooling, and worked as an equipment chief for a telephone company prior to his stroke. SH's lesion includes the left temporal lobe and portions of the left posterior parietal lobe. SH's speech is slightly non-fluent, characterized by slow access and some word-finding difficulties.

Patient SJ. Patient SJ is a 61-year-old right-handed female with a left-hemisphere lesion incurred from a CVA in 2006. She completed 13 years of school, and was employed in public relations prior to her stroke. SJ's lesion affects mostly posterior parietal regions, including both angular gyrus and supramarginal gyrus. Slight posterior superior temporal damage is also present. SJ's speech is fluent, with minimal word-finding difficulties.

Fluency varies across patients. Additionally, all patients showed reduced phonological and semantic short-term retention, as measured by the rhyme and category probe tasks respectively (Table 1). Note that age-matched controls have previously shown rhyme and category probe spans of 7.5 and 6.1 items, respectively (Martin & He, 2004). In contrast, all patients demonstrate relatively intact semantics (Table 1), as measured by single picture naming (Philadelphia Picture Naming Task; Roach, Schwartz, N. Martin, Grewal & Brecher, 1996) and word-picture matching (Martin, Lesch & Bartha, 1999).

Table 1. Patient background, including experiments participated in (Experiments) and performance on STM and semantic measures. Category and rhyme probe spans are measured as the list length at which patient is 75% accurate. Picture naming and word-picture matching values show percent correct.

		STM Measures		Semantic Measures	
	Experiments	Category Probe Span	Rhyme Probe Span	Picture Naming	Word-pic matching
BB	2-4	3.34	1.5	73	94
BQ	1-4	4.17	3.76	87	92
ER	1	2.35	4	90	97
EV	2-4	3.34	1.8	90	95
MB	1-4	5	2.45	77	98
NC	1	3.5	3	93	99
ML	1-4	1.75	1.8	100	99
SH	1-4	2	3	83	98
SJ	2-4	3	2.38	90	97

The category and rhyme probe measures were included to reflect phonological and semantic STM. Evidence for the separation of phonological and lexical-semantic representations in STM comes from neuropsychological research on aphasic patients with selective deficits in maintaining a particular type of information in STM. Martin and colleagues have shown dissociations within aphasic patients with good single word processing abilities and intact semantic knowledge, but reduced STM spans ranging around 1 to 3 items. Like the patients above, these patients tend to show unique patterns of performance on various STM tasks (Martin & He, 2004; Martin et al., 1994; Martin &

Romani, 1994; Romani & Martin, 1999). Patients with a deficit in maintaining phonological information do not show the standard phonological effects in recall. Unlike neurologically healthy subjects, patients with phonological STM deficits do not show a disadvantage for phonologically similar words. Similarly, these patients do not show standard word length effects, suggesting an impairment in phonological maintenance. Additionally, these patients do benefit from semantic information, as their word spans are greater than their nonword spans. These patients also show an advantage for maintaining semantic information, as opposed to phonological information, in probe tasks designed to separately assess the maintenance of each type of information. Patients with phonological STM deficits perform better on the category probe task, in which subjects decide whether the probe item is in the same category as any of the previous list items, compared to a rhyme probe task, in which subjects decide whether the probe item rhymed with any of the previous list items. This pattern of deficits on STM tasks suggests that patients with phonological STM deficits have difficulty retaining phonological information, compared to semantic information. Phonological STM deficits are thought to be caused by an overly rapid decay of phonological information (e.g. N. Martin and Saffran, 1992; R. Martin et al., 1994).

In contrast, patients with semantic STM deficits do show standard phonological effects in list recall. However, they do not show a large advantage for words over nonwords, suggesting they do not benefit from the additional lexical-semantic information in word lists (relative to nonword lists). Additionally, patients with semantic STM deficits perform better on the rhyme probe task, relative to the category probe task. This pattern suggests that patients with semantic STM deficit have difficulty retaining lexical-semantic information in STM. Given their intact semantic knowledge and good single word processing abilities in both patient groups, the dissociation between the two patient types suggests there are separate stores, or buffers, for maintaining phonological and lexical-semantic information in STM (Martin et al., 1994; Martin et al., 1999).

Semantic STM deficits are thought to result from excessive interference of lexical-semantic information (Hamilton & Martin, 2005, 2007; cf. Hoffman et al., 2009). Hamilton and Martin (2005, 2007), for example, found that semantic STM patient ML showed a deficit on verbal, but not nonverbal, inhibition tasks. Specifically, ML showed significantly exaggerated interference effects on a two verbal inhibition tasks (Stroop task, recent negatives probe task), but was within the normal range on two nonverbal inhibition tasks (spatial analogue of the Stoop task, anti-saccade task). Based on this performance dissociation between verbal and nonverbal inhibition tasks, Hamilton and Martin (2005) concluded that semantic STM deficits may be associated with failures of verbal inhibition, suggesting a critical role of executive control in semantic STM.

Experiment 1

Experiment 1 was designed to test patient performance on a fully cued task switching paradigm across several cue-stimulus intervals (CSI), measuring both global and local switch costs. The two goals of this first experiment were as follows: 1) to verify that this task produces the well-replicated effects discussed above for control subjects, 2) to test this task switching paradigm on several patients with STM deficits to determine whether their switch costs are within the normal range in a shifting task with minimal memory demands. According to the claims of Hoffman et al. (2008), one might predict that patients with semantic STM deficits would be impaired on this task-switching task, if a semantic STM deficit results from a global executive function deficit, which would include a deficit in shifting.

Method

Subjects. Sixteen older control subjects (*M* age = 64.4 years; *SD* = 5.6 years) from the local Houston community participated in exchange for monetary compensation ($10/hour). Six aphasic patients with STM deficits also participated in exchange for monetary compensation. Unfortunately, control data on rhyme and category probe measures were not collected the healthy control subjects tested in Experiment 1.

Materials, design, and procedure. Stimuli were presented on a Macintosh computer running PsyScope (Cohen, MacWhinney, Flatt & Provost, 1993). The cued shifting task consisted of two shapes (triangle, square) in two different colors (yellow, blue) of two different sizes (4.5x4.5 cm, 6.5x6.5 cm), totaling eight possible targets (e.g. large yellow square). Targets were displayed one at a time. Target onset was preceded by a cue indicating the relevant task set for the present trial: cues appeared above the target's location and read either "Shape" or "Color". Cue onset occurred at variable intervals before target onset (the cue-stimulus interval, or CSI): 250 ms, 650 ms, 1050 ms. For all trials, the response-cue interval (RCI) was fixed at 500 ms. Participants were asked to respond to the target based on the relevant cued task set; both cue and target remained on the screen until a button press was made. The square shape and the color yellow were mapped to one response key, while the triangle shape and the color blue were mapped to a second response key. The size dimension was irrelevant in the present experiment.

For each CSI, participants completed one set of three blocks: a color pure block, a shape pure block, and a mixed block (in this fixed order); all practice trials were conducted at the 650 CSI. Targets in both pure and mixed blocks were selected pseudo-randomly with the constraint that no exact stimulus repetitions were allowed. For example, if trial n was cued with "Shape," using a large yellow triangle, trial n+1 could not be cued with "Shape," also having a large yellow triangle. However, it was possible for trial n+1 to be cued with "Shape"; likewise, trial n+1's target could be a large yellow triangle if cued with "Color." In pure blocks, participants responded to either "Shape" or "Color" for the duration of the block; each pure block contained 84 trials. In mixed blocks, participants alternated between responding to "Shape" and "Color" task sets on every fourth trial (i.e. the alternating runs paradigm of Rogers & Monsell (1995): $task_1$, $task_1$, $task_1$, $task_1$, $task_2$, $task_2$, $task_2$, $task_2$); each mixed block contained 152 trials. Participants completed one set of three blocks (pure, pure, mixed) for each CSI, with all participants receiving the 250, 650 and 1050 CSIs in fixed order. That is, the order of block and CSI presentations were the same across all participants.

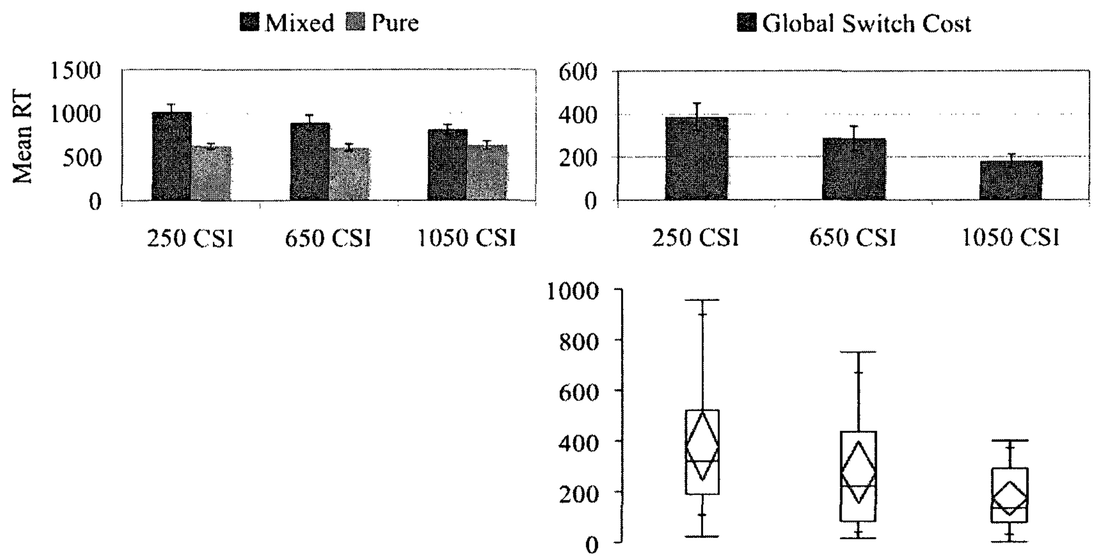
Participants were instructed to respond to the appropriate dimension based on the word cue and using a button press. Participants were first familiarized with the task in three practice blocks: 1 practice pure block for each task (48 trials/block) and 1 practice mixed block (48 trials). Following practice, testing occurred in three sets of three blocks (one set for each CSI), with each set using a fixed CSI (blocked by set). Participants were offered short breaks between sets. Key presses and time taken to complete each trial were recorded electronically with the PsyScope button box.

Results

Data processing. The first 20-24 trials of each block were considered warm-up and excluded from analysis. For all participants, response times (RT) less than 300 ms and greater than 15,000 ms were also excluded from analysis. Additionally, all RTs more than 2.5 standard deviations above or below a participant's mean, by condition, were excluded as outliers. For controls, repeated-measures ANOVAs were calculated on trimmed RTs and errors. Except where otherwise indicated, error analyses produced the same results as RT analyses. RT switch costs were calculated as proportions to optimize comparisons between controls and patients. Global switch costs were calculated as (switch–pure)/pure; local switch costs were calculated as (switch-repeat)/repeat (e.g. Kramer et al., 1999). Error switch costs were calculated as the difference between mixed and pure conditions for global switch costs, and the difference between switch and repeat trials for local switch costs.

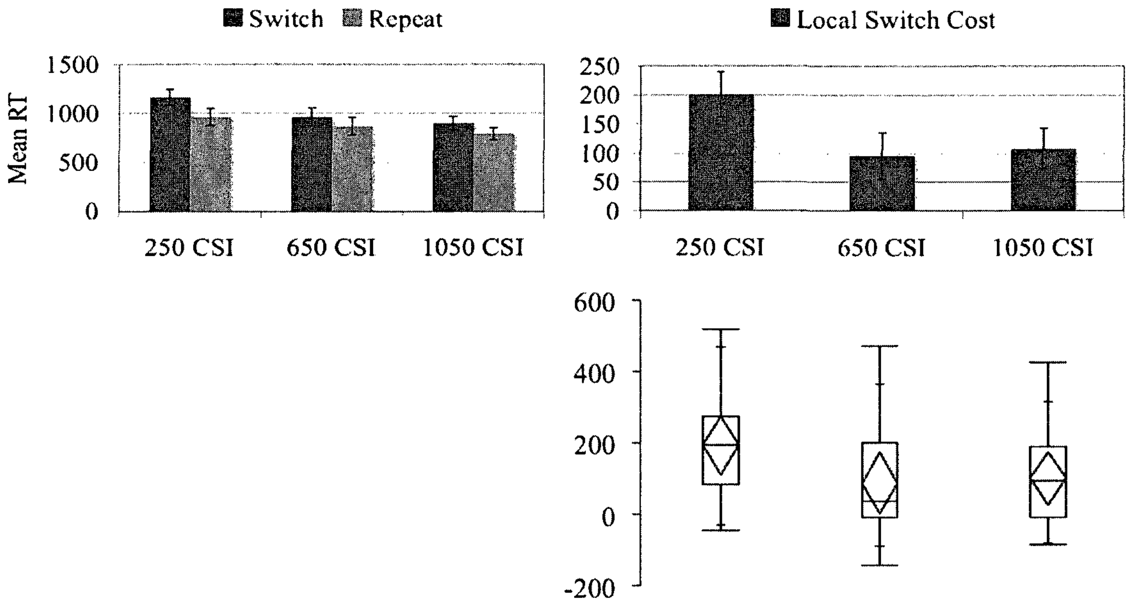
Controls: global switch costs. Figure 1A displays mean response times for mixed and pure block performance (representing global switch costs) across CSI. Subjects were highly accurate across all conditions (M error = 1%). Global switch cost RT data was analyzed in a repeated-measures ANOVA with block (pure, mixed) and CSI (250, 650, 1050) as within-subject factors. The main effect of block was significant ($F(1, 15) = 38.91$, $p < .001$), with slowed RTs in mixed blocks ($M = 906$ ms) relative to pure blocks ($M = 622$). Additionally, RTs significantly decreased as the CSI increased ($F(2, 30) = 12.91$, $p =< .001$), indicating a RT decrease from the 250 CSI ($M = 817$ ms) to the 650 CSI ($M = 750$ ms) to the 1050 CSI ($M = 723$ ms). There was also a significant block x CSI interaction ($F(1.6, 23.4) = 9.87$, $p = .002$), which was further investigated with a priori two contrasts comparing proportional global switch costs a) in the 250 CSI to the 650 CSI, and b) in the 650 CSI to the 1050 CSI. As can be seen in Figure 1B, subjects' global proportional switch costs significantly decreased from the 250 CSI ($M = .60$) to the 650 CSI ($M = .44$; $F(1, 15) = 7.67, p = .01$), as well as from the 650 CSI to the 1050 CSI ($M = 0.29$, $F(1, 15) = 6.91, p = .02$). In the switch cost analyses for errors, there was no significant switch cost reduction from the 650 CSI to the 1050 CSI ($F(1, 15) = 0.31, p = .58$).

Figure 1. Global task switching effects for controls in Experiment 1. Figure 1A (left): mean RTs by block (mixed, pure) and CSI (250, 650, 1050). Figure 1B (right, top): mean global switch costs by CSI. For top figures, error bars depict standard error of the mean. Figure 1B (right, bottom): box plots displaying control switch cost distributions, including minimum and maximum (whiskers), quartiles (box), and median (single line).



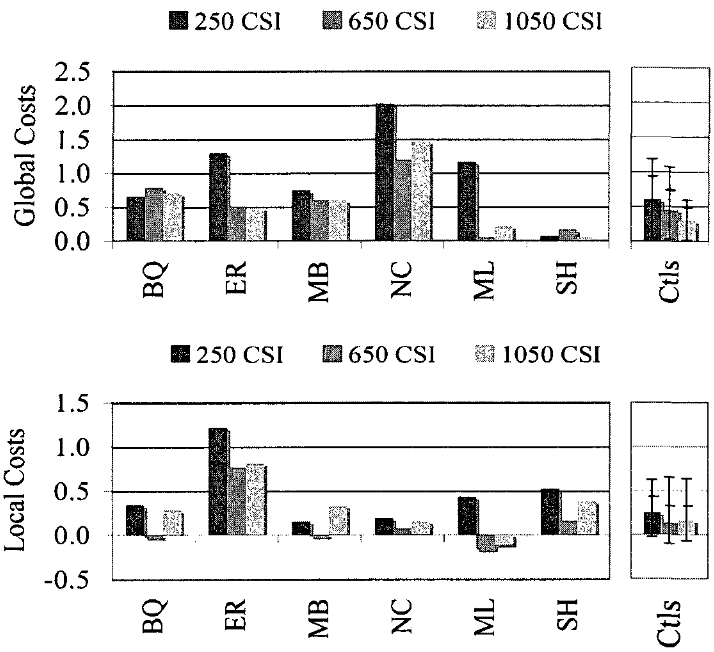
Controls: local switch costs. Figure 2A shows mean response times for switch and repeat trials within the mixed block (representing local switch costs). Again, subjects were highly accurate across all conditions ($M = 2\%$). Local switch cost RT data was analyzed in a repeated-measures ANOVA in which trial (repeat, switch) and CSI (250, 650, 1050) were within-subject factors. There was a significant main effect of trial ($F(1, 15) = 15.31$, $p = .001$), with slowed RTs on switch trials ($M = 1009$) relative to repeat trials ($M = 874$). Additionally, RTs significantly decreased as CSI increased ($F(2, 30) = 16.09$, $p < .001$), indicating a RT decrease from the 250 CSI ($M = 1015$ ms) to the 650 CSI ($M = 892$ ms) to the 1050 CSI ($M = 821$ ms). There was also a significant interaction between trial and CSI ($F(1.69, 25.32) = 8.49$, $p = .002$); this interaction was investigated with two a priori contrasts comparing the proportional local switch costs a) in the 250 CSI to the 650 CSI, and b) in the 650 CSI to the 1050 CSI. As can be seen in Figure 2B, subjects' local proportional switch costs significantly decreased from the 250 CSI ($M = .25$) to the 650 CSI ($M = .13$; $F(1, 15) = 11.61$, $p = .004$), but not from the 650 CSI to the 1050 CSI ($M = .16$; $F(1, 15) = 0.77$, $p = .39$). Similar to the RT analyses, error analyses produced a significant interaction between trial and CSI ($F(2, 30) = 8.49$, $p = .001$); however, neither of the two contrasts comparing local switch costs across the three CSIs was significant (all F's < 1, all p's > .75). In error rates, this interaction appears to be modulated by a slight decrease in errors at the 1050 CSI. However, given the small size of switch cost effects between the three CSIs, this effect did not hold in the contrast analyses.

Figure 2. Local task switching effects for controls in Experiment 1. Figure 2A (left): mean RTs by trial type (switch, repeat) and CSI (250, 650, 1050). Figure 2B (right, top): mean proportional local switch costs by CSI. For top figures, error bars depict standard error of the mean. Figure 2B (right, bottom): box plots displaying control switch cost distributions, including minimum and maximum (whiskers), quartiles (box), and median (single line).



Patients: global switch costs. Comparison of patient and control proportional switch costs can be seen in Figure 3. Figure 3A shows global switch costs. Patient performance was compared to controls using a modified t-test argued to be appropriate for testing whether single cases differ from a control group (Crawford & Howell, 1998). Using this procedure, the standard deviation of a small sample is taken as an estimate of the population standard deviation, and the individual (patient) is treated as a sample of N = 1 (p. 483). Patients and control values are then entered into a t-test formula to determine whether individual cases are beyond the 95^{th} percentile for the control group. Crawford and Howell (1998) have shown this test appropriate for small sample sizes and neuropsychological research. For the present experiments, all t-tests were two-tailed.

Figure 3. Task switching effects for controls (Ctls) and patients in Experiment 1. Figure 3A (top): proportional global switch cost by CSI (250, 650, 1050). Figure 3B (bottom): proportional local switch cost by CSI. Error bars show minimum and maximum for controls and tick marks show standard deviations.



Patient proportional global switch costs and associated t-test statistics are shown in Table 2 (as well as the mean and standard deviation for controls). Of the six patients, only patient NC showed significantly larger switch costs across all three CSIs. Additionally, two patients showed switch costs significantly differing from controls on a single CSI (ER, 250 CSI; BQ, 1050 CSI). As can be seen in Figure 3A, individual patient switch costs across CSI were less consistent than the mean for controls. However, there is still a general pattern of decreased switch cost as a function of increased CSI, with some patients appearing to show a very large benefit of CSI increase from 250 to 1050 (e.g. patients ER, NC, and ML).

Table 2. Proportional global switch costs and t-test statistics for patients, along with the mean and standard deviation (in parentheses) for controls in Experiment 1. Asterisks indicate patient switch costs that differ significantly from controls.

	250 CSI			*650 CSI*			*1050 CSI*		
	M	*t*	*p*	*M*	*t*	*p*	*M*	*t*	*p*

BQ	0.65	0.16	.88	0.79	1.11	.28	0.70	2.27	.04*
ER	1.30	2.18	.05*	0.50	0.19	.85	0.49	1.08	.30
MB	0.74	0.45	.66	0.60	0.50	.62	0.60	1.69	.11
NC	2.02	4.44	.001*	1.20	2.45	.03*	1.46	6.49	<.001*
ML	1.16	1.74	.10	0.05	-1.29	.22	0.21	-0.43	.67
SH	0.07	-1.68	.11	0.16	-0.91	.38	0.05	-1.35	.20
Controls	0.60 (0.31)			0.44 (0.30)			0.29 (0.18)		

Similar to controls, patients made very few errors in this task switching paradigm. Global switch costs, calculated as the difference in errors between mixed and pure blocks, are shown in Table 3. As can be seen, patients not only made very few errors in both block types, but their error switch costs were also minimal, similar to controls. Individual t-tests for each patient confirmed this observation: in switch costs, no patients made significantly more errors than controls.

Table 3. Error rates for global and local switch costs for patients, along with the means and standard deviations (in parentheses) for controls in Experiment 1. Asterisk indicates patient switch cost that differs significantly from controls.

	Global			*Local*		
	Mixed Block	Pure Blocks	Switch Cost	Switch Trials	Repeat Trials	Switch Cost
BQ	0.04	0.01	0.03	0.01	0.06	-0.05*
ER	0.00	0.00	0.00	0.00	0.00	0.00
MB	0.01	0.003	0.01	0.02	0.01	0.01
NC	0.04	0.01	0.03	0.03	0.04	-0.01
ML	0.01	0.01	0.01	0.00	0.02	-0.02
SH	0.00	0.00	0.00	0.00	0.00	0.00
Controls (SD)	0.02 (0.02)	0.01 (0.007)	0.01 (0.01)	0.03 (0.03)	0.02 (0.02)	0.02 (0.02)

Patients: local switch costs. Comparison of patient and control proportional local switch costs can be seen in Figure 3B. For local switch costs, patient performance was again compared to controls using the modified t-test for comparing individual cases to small sample sizes (Crawford & Howell, 1998). Patient proportional local switch costs and associated t-test statistics are shown in Table 4 (as well as the mean and standard deviation for controls). Again, of the six patients, only patient ER showed significantly larger switch costs across all three CSIs. The remaining five patients showed switch costs within the range of controls. As can be seen in Figure 3B, there was a lot of variability in individual patient switch costs across CSI. While there is still a general pattern of decreased switch cost as a function of increased CSI, some patients showed interesting patterns. Patient ML, for example, showed *negative* local switch costs on the 650 and 1050 CSI, suggesting little to no difference between switch and repeat trials. Patients BQ and MB both showed a small negative switch cost at the 650 CSI, but a positive switch cost at the 1050 CSI. And in contrast to the other patients and controls, patient MB showed a larger switch cost at the 1050 CSI. Thus, while individual patient switch costs tended to be statistically similar to controls, patterns of switch costs differed across patients.

Table 4. Proportional local switch costs and t-test statistics for patients, along with the mean and standard deviation (in parentheses) for controls in Experiment 1. Asterisks indicate patient switch costs that differ significantly from controls.

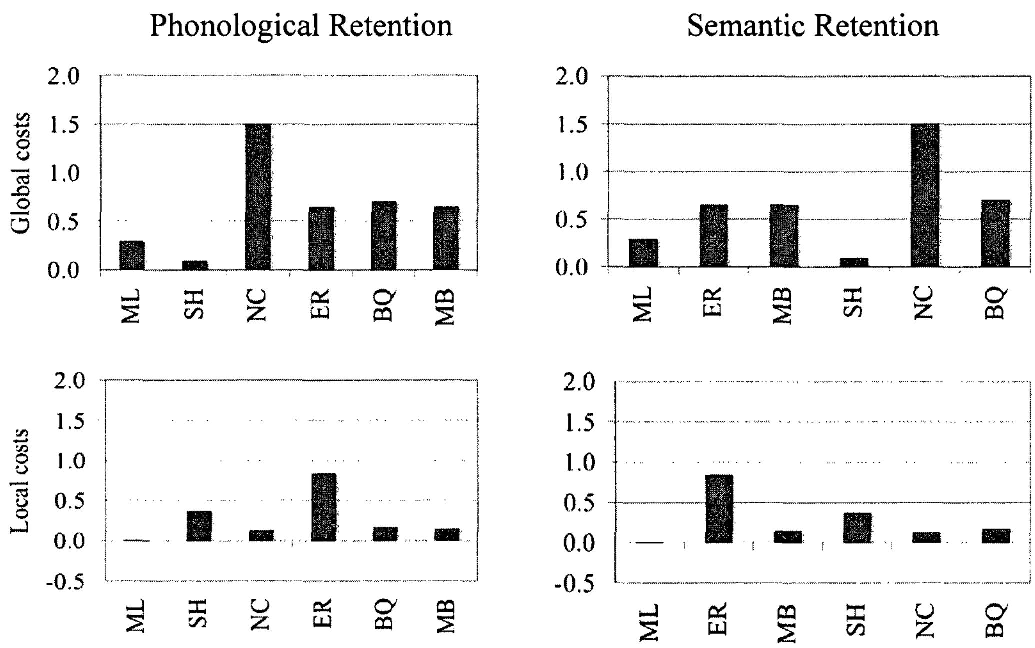
	250 CSI			*650 CSI*			*1050 CSI*		
	M	*t*	*p*	*M*	*t*	*p*	*M*	*t*	*p*
BQ	0.34	0.43	0.67	-0.03	-0.74	0.47	0.28	0.58	0.57
ER	1.22	4.59	<0.001*	0.76	2.82	0.01*	0.81	3.16	0.01*
MB	0.15	-0.46	0.65	-0.02	-0.69	0.50	0.33	0.81	0.43
NC	0.19	-0.29	0.78	0.07	-0.27	0.79	0.15	-0.04	0.97
ML	0.43	0.85	0.41	-0.17	-1.34	0.20	-0.11	-1.34	0.20
SH	0.52	1.28	0.22	0.16	0.12	0.91	0.38	1.06	0.31
Controls	0.25 (0.20)			0.13 (0.22)			0.16 (0.20)		

Local switch costs, calculated as the difference in errors between switch and repeat trials averaged across CSI, are shown in Table 3. Similar to global switch costs and controls, patients not made very few errors in both block types and error switch costs were minimal. For the most part, individual t-tests for each patient confirmed this observation: only patient BQ made significantly more errors than controls.

Relationship between switch costs and short-term retention. As previously mentioned, rhyme and category probe measures were not collected on the control subjects participating in Experiment 1. Therefore, the relationship between switch costs (global and local) and short-term retention (phonological and semantic) is only presented for the patient. Given the small number of patients across all experiments, correlation analyses were deemed inappropriate. Instead, the relationship between shifting measures and short-term retention was examined by ordering patients according to degree of short-term memory deficit, to determine if there was a visible relationship between shifting and span measures.

The relationship between switch costs (averaged across CSI) and phonological (top) and semantic (bottom) retention are shown Figure 4. Patients with the lowest spans are listed first (left side of the x-axis), while patients with the larger spans are listed later (right side of the x-axis). As can be seen in Figure 4, patient global (Figure 4A) and local (Figure 4B) switch costs had no obvious relationship with either phonological or semantic retention, as measured by the rhyme and category probe tasks.

Figure 4. Relationship between switch costs and short-term retention for patients in Experiment 1. Figure 4A (top): Patient global switch costs as a function of phonological (left) and semantic (right) retention. Figure 4B (bottom): local switch costs as a function of phonological (left) and semantic (right) retention.



Experiment 1 Discussion

Experiment 1 investigated the performance of STM patients in a fully cued task switching paradigm across three cue-stimulus intervals. The main goals of this experiment were threefold. First, we wanted to assure that this paradigm and experimental set-up produced the normal, well-replicated effects in normal control subjects. Second, we wanted to determine whether patients with STM deficits were able to perform a fully cued shifting task, given the hypothesis that this task involves little memory demands. Third, given that patients were able to perform this task, we wanted to determine whether patient switching measures – that is, the global and local switch costs – were in the normal range. Is patient shifting ability hampered by short-term memory deficits?

Looking first at the control data, we see that the data from our task switching paradigm clearly replicated previous research. Controls showed both global and local switch costs, suggesting that switching tasks incurs a cost, and is less efficient than performing a single task (e.g. Jersild, 1927; Rogers & Monsell, 1995; Spector & Biederman, 1976). Additionally, these switch costs decreased as a function of the preparatory interval, or CSI (e.g. Allport et al., 1994; Mayr & Keele, 2000; Meiran, 1996; Rogers & Monsell, 1995). Global switch costs decreased with the increase in preparatory interval, such that the shortest switch costs were found at the longest CSIs. The continued global switch cost reduction from the 650 CSI to the 1050 CSI is surprising, given previous research suggesting older adults typically receive no additional preparation benefit beyond ~600 ms (e.g. Kray & Lindenberger, 2000; Meiran, Gotler & Perlman, 2001; Rogers & Monsell, 1995). In contrast, local switch costs decreased from the 250 CSI to the 650 CSI, but there was no significant difference between the 650 CSI and the 1050 CSI. Thus, related to the first goal of the present experiment, this cued shifting paradigm did produce well-replicated effects in healthy, older adults.

The most important finding related to Experiment 1 is related to shifting performance of patients with STM deficits. First, patients had very few problems performing this cue-based shifting paradigm, as evidenced by the very low error rates. More specifically, with the exception of a few cases, patients' switch costs did not significantly differ from controls, suggesting no general shifting impairment in patients with STM deficits. This finding is especially important given that it is in stark contrast to previous research demonstrating patient ML's inability to complete a task switching paradigm using Navon figures and an indirect cueing method. As proposed above, this performance difference may be due to the memory load associated with each task – a hypothesis to be tested in experiments 2-4. As shown in Figures 4A-B, there was no relation between patients' performance on rhyme and category probe tasks and the size of either global or local switch costs. These results are in accord with those from a study with a larger group of patients (Allen, R. Martin and N. Martin, in preparation) that found no relationship between this cued shifting task (global measures, at the 650 ms CSI) and short-term memory (i.e. rhyme probe, category probe, word span, digit span) in a sample of 19 aphasic patients. In contrast, there was a relationship between short-term retention and other components of executive function, such as updating (e.g. Miyake et al., 2000).

The finding of impaired shifting (relative to controls) across all CSIs in patients NC (global switch costs) and ER (local switch costs) is unlikely to be due to their STM deficits, as patients with small STM spans showed smaller (i.e. better) switch costs. Similarly, this impaired performance is unlikely to be caused by an inhibition deficit, as patient ML – hypothesized to have a deficit in verbal inhibition (Hamilton & Martin, 2005, 2007) – performed normally on this shifting task.

Instead, it may be hypothesized that patient NC has a specific difficulty with some aspect of global shifting, while ER has a specific difficulty with some aspect of local shifting. This hypothesis is supported by each patient's performance on a similar switching task (unpublished research from our lab). In a word version of this same cued shifting task, the target is a one-syllable word. Subjects are instructed to indicate whether the word's referent is living or non-living ('Life' task) or small or large ('Size' task), depending on the cue. On this task, NC's global switch costs were significantly longer than controls for both the 250 and 650 CSI, but not for the 1050 CSI. In contrast, his local switch costs did not significantly differ from controls. And similar to the results of the present experiment, ER's local switch costs were significantly longer than controls for all three CSIs, while her global switch costs did not significantly differ from controls. Thus, the findings in the word version of this cued shifting task, for these two patients, replicate the findings from the shape version described above.

As previously stated, global and local switch costs are hypothesized to tap different processes (e.g. Kray & Lindenberger, 2000; Mayr, 2001), and the patient dissociations between these two costs further support this notion. If global and local switch costs tapped the same process, we would expect a patient impaired in one to also be impaired in the other. Instead, the double dissociation in these two patients supports the hypothesis that these two shifting components do, in fact, represent distinct processes. NC's difficulty with global switching may reflect an inability to effectively update multiple task sets in working memory, while his ability to execute task shifts (local switching) is relatively unimpaired. In contrast, the reverse applies for patient ER – her difficulty with local switching may reflect an impaired ability to execute task shifts, involving task set reconfiguration, with spared ability to maintain multiple task sets in working memory. However, this hypothesis is speculative, given the similarity of the two tasks on which these two patients have been tested. A better test of this hypothesis would require assessing shifting ability in a different switching paradigm with minimal STM demands. While these would be important issues to address in future research, they are outside the scope of the work proposed here.

Nonetheless, the fact that the majority of patients with short-term memory deficits performed similarly to controls on a fully cued shifting task suggests that ML's difficulty associated with the Navon figures task switching paradigm was not due to a deficit in shifting per se, but perhaps to some aspect of the task requirements themselves. The remaining experiments investigate the hypothesis that these task demands are related to the task's memory load.

Experiments 2-4

The three following experiments investigated the hypothesis that shifting abilities interact with WM load, in both patients with STM deficits and healthy controls. To test this hypothesis, WM load was varied across three experiments. Like Experiment 1, Experiment 2 utilized full cues to indicate what task should be performed on a given task; the differences between Experiment 2 and Experiment 1 are described below. In Experiments 3 and 4, the shifting task's WM load was increased through cue processing demands. In Experiment 3, subjects were required to retain cue-based information and in Experiment 4, subjects were required to process symbolic cues. To the extent that these manipulations increase demands on phonological STM, patient performance decrements should be greater in Experiments 3 and 4 than in Experiment 2. Additionally, Experiments 2-4 also assessed WM demands by investigating the effects of selectively impairing phonological STM through articulatory suppression (Baddeley, Lewis & Vallar, 1984). Finding that suppression affects the shifting performance of normal older adults, as found in young college-aged students, would provide further support for a role for phonological STM in shifting processes (e.g. Baddeley et al., 2001; Emerson & Miyake, 2003; Miyake et al., 2004). Patient performance should be more similar to that of controls in the articulatory suppression condition than in the standard no-suppression condition.

Method

Subjects. Twenty control subjects from the Houston-area community were tested in Experiments 2, 3, and 4 (within-subjects), in exchange for monetary compensation. On average, control subjects were 64.5 years old (*SD* = 6.3, range: 56-76) and had 16.7 years (*SD* = 1.8, range: 14-20) of education. All 20 control subjects were able to complete Experiments 2 and 3; only one subject was unable to return for Experiment 4. Controls participated in both standard condition and articulatory suppression (AS) condition, with the test order (standard-AS, or vice versa) counterbalanced across subjects. Seven aphasic patients from our lab at Rice University also participated in exchange for monetary compensation. Patient descriptions are provided in the Patient Background section. Note that neither ER nor NC (described previously) were available for testing in the below experiments.

Materials, design and procedure. Experiments 2, 3 and 4 used the cued shifting task described in Experiment 1, with a few differences. First, the mixed block was composed of alternating runs of trials that switch task sets every two trials (as opposed to every four trials, as in Experiment 1). This increased the number of switch trials within the mixed block, and ensured an equal number of switch and repeat trials for calculating local switch costs. Each pure block contained 88 trials, and each mixed block contained 152 trials (76 switch, 76 repeat). Secondly, Experiments 2-4 used only two CSIs – the 250 ms CSI and 650 ms CSI – given that previous research has found little switch cost reduction beyond a ~600 ms preparation interval (e.g. Allport et al., 1994; Mayr & Keele, 2000; Meiran, 1996; Rogers & Monsell, 1995). Third, Experiments 2-4 manipulated the task's memory load by changing the duration (Experiment 3) and explicitness

(Experiment 4) of the cue. Experiment 2 was similar to Experiment 1 in that it used a word cue that remained on the screen throughout the duration of the trial; this experiment served as a control condition for Experiments 3 and 4. In Experiment 3, the cue was presented *only* during the CSI (either 250 ms or 650 ms), disappearing with target onset. This required participants to maintain the relevant task set *while* performing the task. Experiment 4 investigated the effect of less explicit cues, using nonverbal nonsense symbols (instead of words) to represent each task set. Although these symbols remained on the screen throughout the duration of the trial, they included the added requirement of cue interpretation before task performance could proceed.

One final difference between Experiment 1 and Experiments 2-4 is the addition of an articulatory suppression (AS) condition for control subjects. For each experiment, all controls were tested in both standard and AS conditions to determine whether AS differentially affects shifting abilities, as a function of memory load (as suggested by previous research). In this suppression condition, controls were instructed to say the word "the" once every 750 ms, as paced by a metronome. In the standard condition, the metronome beat was present, but participants were told to ignore it. Test order (standard, AS or the reverse order) was counterbalanced across subjects.

As in Experiment 1, participants received one set of practice trials for each block type, before beginning the experimental trials: pure color, pure shape, and mixed, all administered at the 650 ms CSI. When in the AS condition, controls also practiced saying the word "the" for 25 seconds before beginning the task switching practice. Following practice, all participants completed two sets of three blocks (pure color, pure shape, mixed, first at the 250 CSI, then at the 650 CSI). The first 24 trials of each critical block were considered warm-up, and excluded from analysis.

All healthy adults that participated in Experiments 2-4 also completed the category and rhyme probe tasks to measure the short-term retention of semantic and phonological information (Martin et al., 1994; Martin & He, 2004). Patients have been previously tested on this task (see Patient Background section for patient spans). For patients, testing began at one-item lists and continued until patients scored less than 75% correct on a given list length. Linear interpolation was used to determine at what list length patients would be 75% accurate. Controls, in contrast, were tested on list lengths 4-7 and performance was measured by looking at proportion correct across the four lists. Each list length contained 24 lists, with half yes trials and half no trials. Items in the category probe task came from 10 different categories, with each category containing 24 items. All categories and category members were presented before the start of the task to familiarize subjects with each item's correct category classification. In both tasks, subjects heard a list of words followed by a probe word. In the category probe task, subjects pressed yes if the probe item was in the same category as any of the list items, or no if the probe item was not in the same category as any of the list items. In the rhyme probe task, subjects pressed yes if the probe word rhymed with any list items, or no if there was no rhyme.

Analyses. The data processing and basic analyses in Experiments 2-4 were similar to Experiment 1, unless otherwise noted. For each experiment, repeated measures ANOVAs were run on control data to investigate global and local switching performance, separately for RTs and errors. Global and local switch costs were investigated in separate repeated-measures ANOVAs with suppression (standard, AS), block or trial type (global, block: mixed, pure; local, trial type: switch, repeat) and CSI (250, 650) as within-subject factors. These analyses also initially contained test order (standard-AS or the reverse order) as a between-subjects factor to ensure that suppression counterbalancing was not affecting the pattern of results.

Patient switching performance was assessed by computing proportional switch costs for each CSI, and comparing these values to control switch costs using the modified t-test described in Experiment 1 (Crawford & Howell, 1998); all t-tests were two-tailed. Patient switch costs were compared to controls using the standard condition as the control group. Overall, these analyses will determine whether cue manipulations differentially affect patients relative to control subjects.

After testing, it was found that one control subject made substantially more errors than controls in five of the six testing sessions, despite appearing to have an understanding of the task when asked. Across the three experiments (averaged over all conditions), this subject made errors on 19% of the trials, whereas the remaining controls only made errors on 4% of the trials (*SD* = 3%). This subject was therefore excluded from all analyses, resulting in 19 control subjects in Experiments 2-3, and 18 in Experiment 4.

Experiment 2

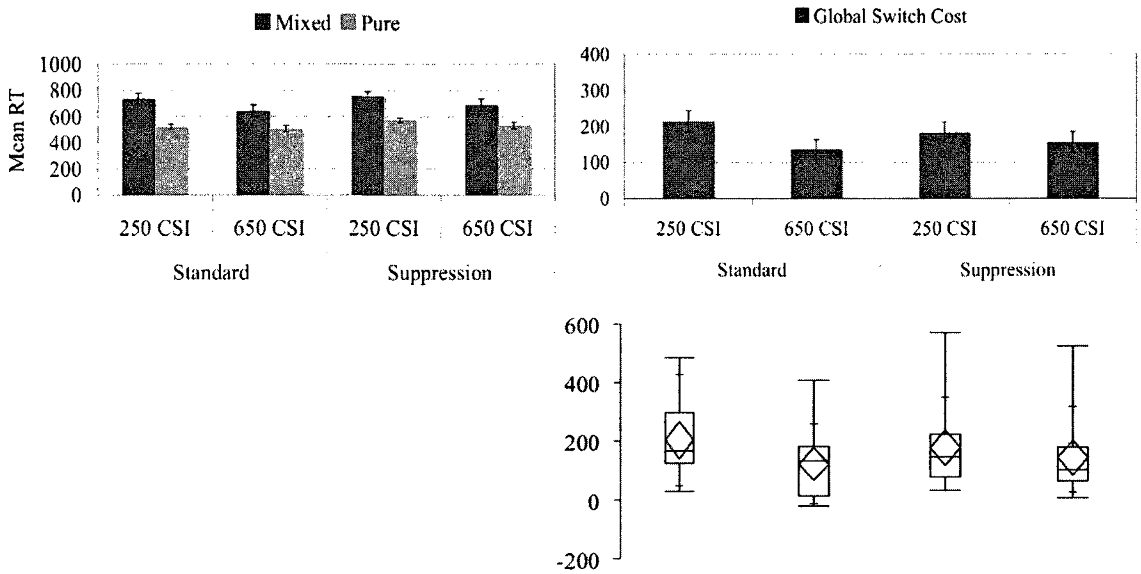
Overview and predictions

Experiment 2 bears many similarities to Experiment 1, with a few exceptions. First, mixed trials are composed of an even number of switch and repeat trials, such that only two trials of a single task are performed before a task switch ($task_1$, $task_1$, $task_2$, $task_2$, $task_1$, $task_1$, etc.). The data from this experiment will serve as a control condition for Experiments 2 and 3, which both manipulate WM demands. Based on previous research, controls were expected to show significant block x CSI interactions, such that switch costs decrease with increases in the preparatory interval. However, similar to Miyake and colleagues (Emerson & Miyake, 2003; Miyake et al., 2004), we predicted little effect of AS on switch costs (beyond a possible main effect), insofar as controls would not show a suppression x block interaction: subjects were not expected to show increased switch costs as a function of AS due to the cue's explicit nature (Emerson & Miyake, 2003; Miyake et al., 2004; but see Bryck & Mary, 2005). Similarly, based on the patient results from Experiment 1, most patients were expected to perform within the range of controls in Experiment 2, a full cueing condition.

Results

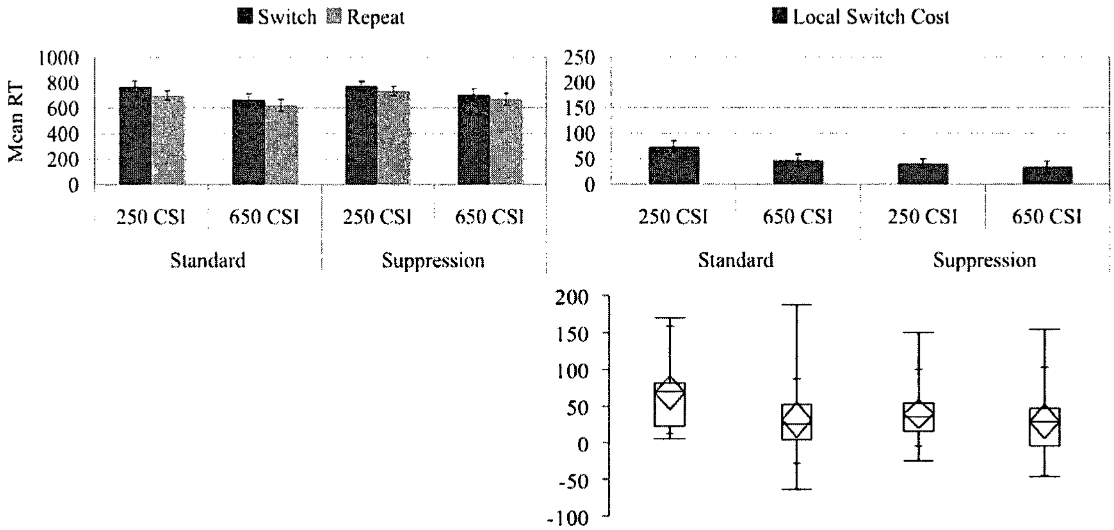
Controls: Global switch costs. Figure 5A displays mean response times for mixed and pure blocks, across CSIs for the standard and AS conditions; the difference between these mixed and pure blocks is the global switch cost. Overall, subjects were highly accurate across all conditions (*M* error = 4%). There was no main effect of test order in RTs or errors (both *p*'s > .60). As expected, there was a main effect of block in both RT ($F(1, 17) = 42.93, p < .001$) and error rates ($F(1, 17) = 51.97, p < .001$), as subjects were slower and more error prone in mixed blocks (*M* = 706 ms, 5%) relative to pure blocks (*M* = 532 ms, 2%), a difference that represents the global switch cost. There was also a main effect of suppression in both RTs and errors ($F(1, 17) = 8.34, p = .01$; $F(1, 17) = 16.19, p = .001$), as subjects were slower and more error prone in the AS condition (M = 633 ms, 5%) relative to the standard condition (M = 598 ms, 2%). Replicating standard preparation effects, there was a significant block x CSI interaction in RTs ($F(1, 17) = 15.63, p = .001$), though this interaction only approached significance in error rates ($F(1, 17) = 3.23, p = .09$): switch costs decreased from the 250 CSI to the 650 CSI (M decrease = 54 ms, 2%; $t(18) = -4.12, p < .001$). Importantly, as predicted, there was no two-way suppression x block interaction in RTs or errors ($F(1, 17) = 0.00, p = .99$; $F(1, 17) = 1.80, p = .20$), as switch costs in the AS condition (M = 172 ms, 3%) did not differ from costs in the standard condition (M = 175 ms, 2%). There was a two-way suppression x test order interaction in RTs that was driven by a three-way suppression x block x test order interaction ($F(1, 17) = 8.62, p = .009$). When subjects completed the AS condition before the standard condition, switch costs were larger in the AS (M = 186 ms) relative to the standard condition (M = 133 ms; $t(8) = -3.04, p = .02$). In contrast, when subjects completed the standard condition before the AS condition, switch costs showed the reverse pattern, being larger in the standard (M = 204 ms) than AS condition (M = 155 ms; though not significantly so, $t(9) = 1.77, p = .11$). In errors, none of the interactions with test order reached significance. Lastly, there was also a three-way suppression x block x CSI interaction in RTs ($F(1, 17) = 4.46, p = .05$), but not errors ($F(1, 17) = 1.50, p = .24$). As can be seen in Figure 5B, there was a greater RT switch cost decrease in the standard condition from the 250 to 650 CSI (78 ms decrease; $t(18) = 4.53, p < .001$) than in the AS condition (27 ms decrease; $t(18) = 1.86, p = .08$).

Figure 5. Global task switching effects for controls in Experiment 2. Figure 5A (left): mean RT by block (mixed, pure) and CSI (250, 650). Figure 5B (right, top): mean global switch costs by CSI. For top figures, error bars depict standard error of the mean. Figure 5B (right, bottom): box plots displaying control switch cost distributions, including minimum and maximum (whiskers), quartiles (box), and median (single line).



Controls: Local switch costs. Figure 6A displays mean response times for repeat and switch trials across CSIs for the standard and AS conditions; the difference between these switch and repeat blocks is the local switch cost. Subjects were highly accurate across all conditions (*M* error = 5%). There was no main effect of test order in RTs or errors (both *p*'s > .60). The main effect of trial type was significant in both RT ($F(1, 18) = 38.67, p < .001$) and error rates ($F(1, 18) = 16.91, p = .001$), as subjects were slower and more error prone on switch trials (*M* = 730 ms, 8%) relative to repeat trials (*M* = 681 ms, 4%). There was a main effect of suppression in RT and error analyses ($F(1, 17) = 4.53, p = .05$; $F(1, 17) = 10.73, p = .004$). In general, subjects were slower and more error prone in the AS condition (*M* = 721 ms, 8%) relative to the standard condition (*M* = 688 ms, 5%). There was also no significant trial type x CSI interaction in RT or error analyses ($F(1, 17) = 1.28, p = .27$; $F(1, 17) = 3.30, p = .09$). In RTs and errors, switch costs decreased from the 250 CSI (*M* = 57 ms, 4%) to the 650 CSI (*M* = 41 ms, 2%), though not significantly. Again, importantly, the suppression x trial type interaction was significant in neither RT nor error rates ($F(1, 17) = 1.34, p = .26$, $F(1, 17) = 3.62, p = .07$). Thus, while subjects were slower and more errors in the AS condition overall, switch costs in the AS condition (*M* = 38 ms, 4%) did not differ from costs in the standard condition (*M* = 60 ms, 3%). Additionally, the two-way suppression x test order interaction in RTs was driven by a three-way suppression x trial type x test order interaction in RTs ($F(1, 17) = 8.62, p = .009$). When subjects completed the AS condition before the standard condition, switch costs were larger in the AS (*M* = 37 ms) relative to the standard condition (*M* = 28 ms), though not significantly so ($t(8) = -1.65, p = .14$). In contrast, when subjects completed the standard condition before the AS condition, the reverse pattern was true – switch costs were larger in the standard (*M* = 72ms) relative to the AS condition (*M* = 36 ms), though again the difference was not significant ($t(9) = 1.99, p = .08$). This same three-way interaction in errors was driven by a four-way suppression x trial type x CSI x test order interaction. When subjects received the AS condition before the standard condition, error switch costs did not change as a function of CSI in either the AS (*M* decrease = -2%) or standard conditions (*M* decrease = 1%). In contrast, when subjects received the standard condition before the AS condition, error switch costs decreased as a function of CSI in both the AS (*M* decrease = 5%, $t(9) = -2.54, p = .03$) and standard conditions (*M* decrease = 3%, $t(9) = -3.79, p = .004$). Lastly, the three-way interaction between suppression, trial type, and CSI was significant in RTs, but not errors ($F(1, 17) = 4.29, p = .05$; $F(1, 17) = 0.22, p = .65$). As can be seen in Figure 6B, RT switch costs in the standard condition decreased from the 250 to 650 CSI (*M* decrease = 37 ms; $t(18) = -2.53, p = .02$), but not in the AS condition (M decrease = 10 ms; $t(18) = -1.26, p = .22$).

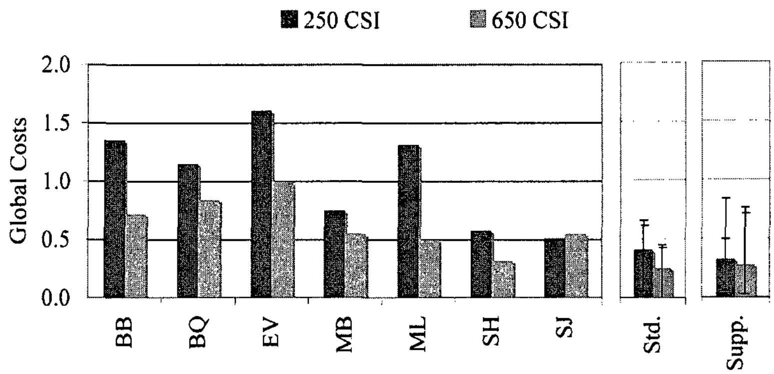
Figure 6. Local task switching effects for controls in Experiment 2. Figure 6A (left): mean RT by block (mixed, pure) and CSI (250, 650). Figure 6B (right, top): mean local switch costs by CSI. For top figures, error bars depict standard error of the mean. Figure 6B (right, bottom): box plots displaying control switch cost distributions, including minimum and maximum (whiskers), quartiles (box), and median (single line).



Patients: global switch costs. Comparisons of patient and control proportional global switch costs are shown in Figure 7A, with costs and associated t-test statistics shown in Table 5. Given that both global and local switch costs for controls under AS were numerically smaller than costs in the standard condition, we only compared costs to control costs in the standard condition. In light of the Experiment 1 results, where all patients except one showed normal global switch costs, it was surprising to find that three of the seven patients (BB, BQ, and EV) in the present experiment showed significantly larger switch costs than controls across both CSIs. Patient ML also showed switch costs significantly greater than controls in the 250 CSI, but not the 650 CSI. As can be seen in

Figure 7A, individual patient switch costs across CSI were greater than the costs shown by controls. However, patients still tended to show a pattern of decreased switch cost as a function of increased CSI, with some patients appearing to show a very large benefit of CSI increase (e.g. patients BB, BQ, EV, and ML).

Figure 7. Task switching effects for controls (in standard (Std.) and suppression (Supp.) conditions) and patients in Experiment 2. Figure 7A (top): proportional global switch cost by CSI (250, 650). Figure 7B (bottom): proportional local switch cost by CSI. Error bars show minimum and maximum for controls and tick marks show standard deviations.



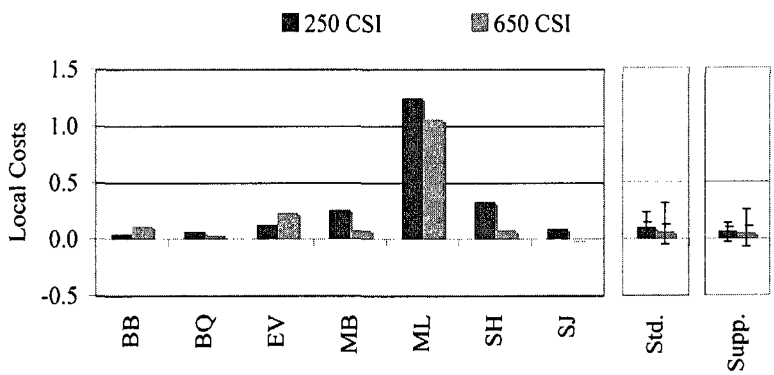


Table 5. Proportional global switch costs and t-test statistics for patients, along with the mean and standard deviation (in parentheses) for controls in the standard and AS conditions in Experiment 2. Asterisks indicate patient switch costs that differ significantly from controls.

	250 CSI			*650 CSI*		
	M	*t*	*P*	*M*	*t*	*p*
BB	1.35	4.03	<.001*	0.71	2.29	.03*
BQ	1.15	3.16	.005*	0.84	2.92	.009*

EV	1.60	5.12	<.001*	0.99	3.64	.002*
MB	0.75	1.44	.17	0.55	1.47	.16
ML	1.31	3.85	.001*	0.49	1.21	.24
SH	0.57	0.68	.51	0.32	0.33	.75
SJ	0.51	0.41	.69	0.54	1.46	.16
Controls, standard	0.41 (.23)			0.25 (.20)		
Controls, suppression	0.32 (.20)			0.28 (.18)		

Although the patients tended to be slower than controls, patients made very few errors in this task switching paradigm. Patient error rates in mixed and pure blocks, as well as global switch costs, are shown in Table 6. Similar to controls, patients made very few errors in both block types. Individual t-tests for each patient confirmed this observation: in error rates (for mixed, pure, and switch costs), no patients differed significantly from controls.

Table 6. Error rates for global and local switch costs for patients, along with the mean and standard deviation (in parentheses) for controls in the standard and AS conditions in Experiment 2.

	Global			*Local*		
	Mixed Block	Pure Blocks	Switch Cost	Switch Trials	Repeat Trials	Switch Cost
BB	0.04	0.04	0.00	0.02	0.05	-0.02
BQ	0.02	0.01	0.01	0.02	0.02	0.01
EV	0.04	0.01	0.02	0.04	0.04	0.00
MB	0.00	0.01	-0.01	0.00	0.00	0.00
ML	0.04	0.00	0.03	0.04	0.03	0.01
SH	0.00	0.00	0.00	0.00	0.00	0.00
SJ	0.01	0.01	0.00	0.01	0.01	0.00
Controls, standard	0.04 (0.03)	0.02 (0.01)	0.02 (.02)	0.05 (0.04)	0.03 (0.03)	0.02 (0.03)
Controls, suppression	0.06 (.03)	0.03 (.02)	0.03 (.01)	0.008 (.04)	0.05 (.03)	0.04 (.04)

Patients: local switch costs. Comparison of patient and control proportional local switch costs can be seen in Figure 7B. For local switch costs, patients were compared to controls using Crawford & Howell's (1998) modified t-test. Patient proportional local switch costs and associated t-test statistics are shown in Table 7, with the standard control condition serving as the patient comparison. Of the seven patients, only patient ML showed significantly larger switch costs across both CSIs. Additionally, two patients (MB, EV) showed significantly larger switch costs at a single CSI (MB at the 250 CSI, EV at the 650 CSI). The remaining patients showed switch costs within the range of controls. As can be seen in Figure 7B, there is still a general pattern of decreased switch cost as a function of increased CSI. Two patients' (BB, EV) switch costs did not decrease as a function of CSI. However, it should be noted that several controls also showed this reverse pattern, and the difference between the blocks for these patients is minimal.

Table 7. Proportional local switch costs and t-test statistics for patients, along with the mean and standard deviation (in parentheses) for controls in the standard and AS conditions in Experiment 2. Asterisks indicate patient switch costs that differ significantly from controls.

	250 CSI			*650 CSI*		
	M	*t*	*p*	*M*	*t*	*p*
BB	0.04	-1.04	.31	0.11	0.62	.54
BQ	0.06	-0.62	.54	0.03	-0.38	.71
EV	0.12	0.38	.71	0.23	2.06	.05*
MB	0.25	2.60	.02*	0.08	0.25	.81
ML	1.25	19.26	<.001*	1.06	11.99	<.001*
SH	0.33	3.79	.001	0.08	0.19	.85
SJ	0.09	-0.21	.84	0.00	-0.74	.47
Controls, standard	0.10 (.06)			0.06 (.08)		
Controls, suppression	0.06 (.06)			0.05 (.07)		

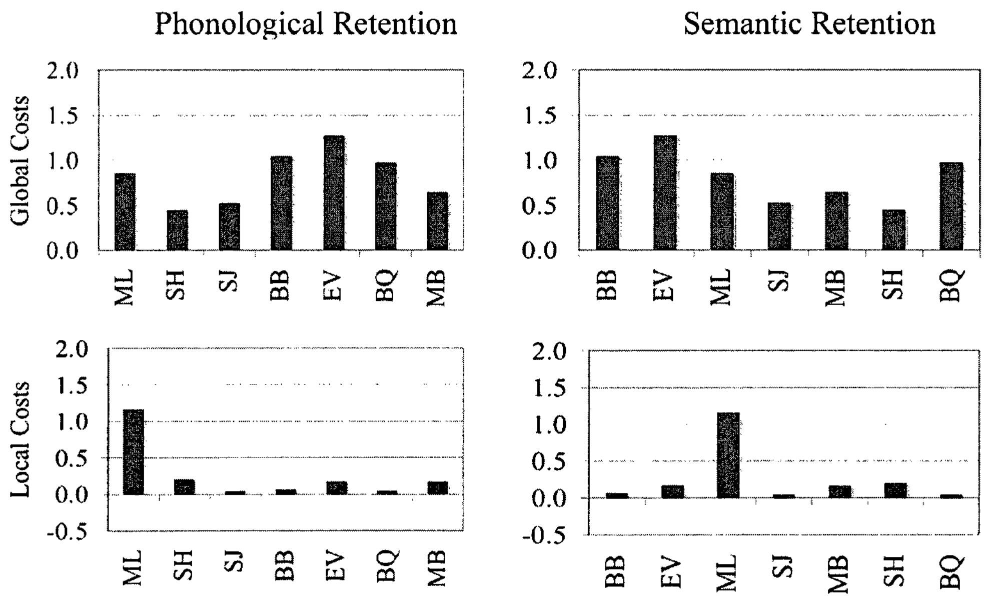
Local switch costs in errors, calculated as the difference in errors between switch and repeat trials averaged across CSI, are shown in Table 6 (above). Similar to controls, patients made very few errors in both trial types, demonstrating minimal switch costs. Individual t-tests for each patient confirmed this observation: none of the patients made significantly more errors than controls.

Relationship between switch costs and short-term retention. Lastly, we wanted to determine whether switch costs were differentially related to phonological or semantic retention. For controls, we did so by correlating global and local switch costs with phonological and semantic retention. Additionally, because there was a significant correlation between phonological and semantic retention for controls ($r = .53$, $p = .02$), we used multiple regression to look at the independent contributions of phonological and semantic retention to switch costs. If either measure of short-term retention were related to switch costs, we would expect a negative correlation – that is, subjects with larger STM capacities show smaller (i.e. better) switch costs. For patients, we used the same descriptive method described in Experiment 1: we arranged patients from lowest to highest span (along the x-axis), and looked to see if span showed any revealing relationship with switch costs.

For controls, global switch costs correlated with neither the rhyme probe ($r = -.09$, $p = .70$) nor the category probe ($r = .15$, $p = .54$), suggesting switch costs in this low WM load condition are not related to short-term retention. As might be expected based on the pairwise correlations, neither STM measure made significant, independent contributions to the global switch cost (both p's > .30). Additionally, as seen in Figure 8A (top), patient global switch costs had no obvious relationship with either phonological or semantic retention.

Likewise, controls' local switch costs correlated with neither rhyme probe (r = .09, p = .73) nor category probe (r = .27, p = .26). Again, neither measure made significant, independent contributions to switch cost prediction (both p's > .25). Patient relationships are shown in Figure 8B (bottom). Although patient ML had the largest local switch cost, there appears to be no obvious relationship between switch costs and either phonological or semantic retention.

Figure 8. Relationship between switch costs and short-term retention for patients in Experiment 2. Figure 8A (top): Patient global switch costs as a function of phonological (left) and semantic (right) retention. Figure 8B (bottom): Patient local switch costs as a function of phonological (left) and semantic (right) retention.



Experiment 2 utilized a full cueing condition in which the cue was a word that remained on the screen throughout the duration of the trial. Given the explicitness of this cue, and its presence throughout the trial, this task switching condition incurs minimal WM demands. Looking at the control data, the results of Experiment 2 were generally in line with previous shifting research. As expected, both global and local switch costs significantly decreased as subjects were given more time to prepare for the upcoming trial, replicating the preparation effect (e.g. Allport et al., 1994; Mayr & Keele, 2000; Meiran, 1996; Rogers & Monsell, 1995). More relevant to the goals of the present study are the effects of AS on switch costs. Neither global nor local switch costs interacted with suppression, suggesting that shifting was not affected by AS, replicating findings in college-aged students (e.g. Baddeley et al., 2001; Miyake et al., 2004). Interestingly, AS did have different effects on global and local costs, as a function of test order – however, these results are not necessarily problematic. Irrespective of test order (standard, AS – or vice versa), subjects were faster in whichever condition was tested second (relative to the first). This suggests that this interaction results from condition-related practice effects, as opposed to test order effects that merit further investigation. Given this, we can focus on the fact that across both test orders, AS did not result in increased switch costs. In fact, switch costs tended to be lower in the AS condition, relative to the standard condition (though not significantly so). Critically, the finding that suppression does not result in increased switch costs suggests that inner speech is not important when task sets are explicitly activated. Supporting this, global and local switch costs did not correlate with measures of short-term retention, suggesting little relationship between task switching and short-term retention in this low WM load shifting condition.

Interestingly, global and local switch costs showed different CSI effects, as a function of suppression. Switch costs significantly decreased across the CSIs in the standard condition, but this decreases was not significant in the AS condition. It is possible that this decrease would reach significance, with more subjects. However, this interaction also raises the possibility that disrupting the phonological processes involved in task switching slows cue processing (even when explicit), such that the 650 CSI does allow enough time for subjects to be fully prepared for the upcoming task set. As such, costs at this CSI look similar to the costs at the 250 CSI. This possibility will be further discussed in the General Discussion.

Unlike the control results, the patient results from this fully cued shifting paradigm are less clear. Given the results of Experiment 1, we expected patients to, for the most part, show effects within the range of controls. Instead, BB, BQ, and EV all had significantly greater switch costs than controls in both CSIs, with ML showed greater costs in the 250 CSI only. Similarly, with local costs, ML showed greater costs than controls in both CSIs, and both EV and MB showed greater costs in a single CSI. The surprising aspect of this data is the comparison to Experiment 1 where, for the most part, patients performed within the range of controls. There are only two major design differences between Experiments 1 and 2. First, Experiment 2 included a metronome beat in the background, which patients were told to ignore; this is unlikely to be the source of exaggerated patient switch costs. The second difference was in the frequency of switches in the mixed block – Experiment 1 switched every four trials (AAAABBBB), while Experiment 2 switched every two trials (AABB). Critically, this second change in itself arguably increases the WM demands of the task – the more frequent the switches, the more often task sets most be updated (in global switching costs) and task set shifts must be executed (in local switching costs). However, most of these patients have also performed several iterations of Experiment 1, in previous research. In fact, their participation in Experiment 2 is the first time they completed this version of the shifting paradigm. Thus, while it is possible that the difference in patient performance across Experiments 1 and 2 is related to the change in WM demands, the effects could also result from changes in task methodologies, relative to what the patients had done before. Despite the cause of the difference, it should be noted that patient switch costs in the present experiment showed no clear relation with any measure of short-term retention. Lastly, patient differences only appeared in RT analyses, and not errors. In fact, like controls, patients made *very* few errors on this task, across all block and trial types, similar to Experiment 1.

Experiment 3

Overview and predictions

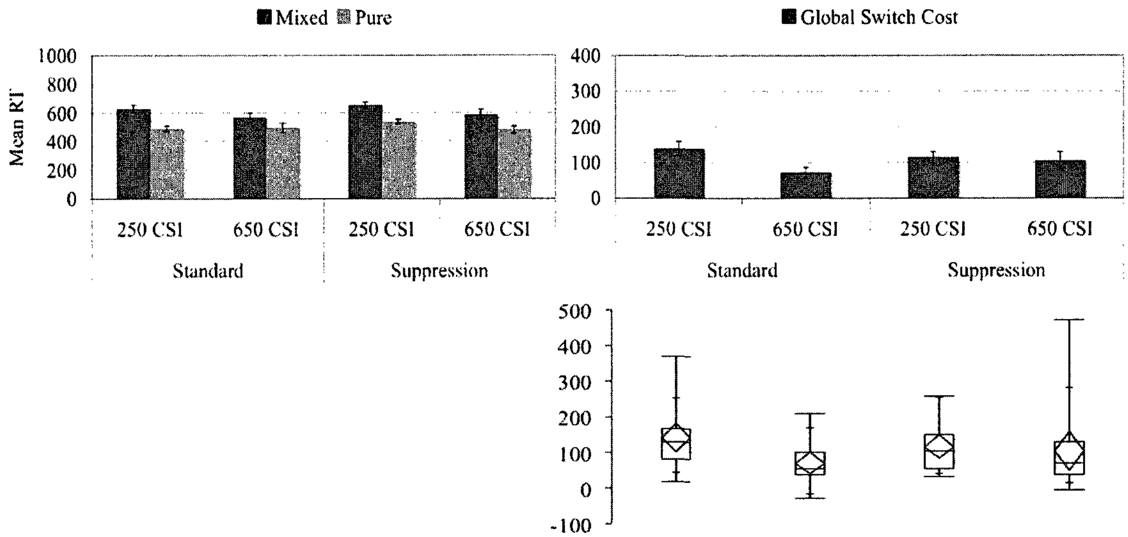
Experiment 3 bears many design similarities to Experiment 2, with one exception: the cue, indicating which task is to be performed on a given trial, is only presented during the CSI – that is, during the 250 or 650 ms prior to target onset. This cue manipulation is designed to slightly increase the task's WM demand, as participants are required to retain cue-based information upon target presentation. While minimal, the lack of cue presence throughout the duration of the trial does increase memory demands, though we predicted little to no effect of AS on controls' switch costs (beyond a main effect),. In contrast, we predicted that patients would be affected by the additional cue retention requirement such that they would show increased switch costs relative to Experiment 2.

Results

Controls: Global switch costs. Figure 9A displays mean response times for mixed and pure blocks, across CSIs for the standard and AS conditions; the difference between these mixed and pure blocks is the global switch cost. Overall, subjects were highly accurate across all conditions (*M* error = 5%). There were no main effects of test order (all *p*'s > .50). There was a significant main effect of block in both RT and error rates ($F(1, 17) = 53.66, p < .001$; $F(1, 17) = 49.09, p < .001$), as subjects were slower and more error prone in mixed blocks ($M = 608$ ms, 7%) relative to pure blocks ($M = 501$ ms, 4%). There was also a main effect of suppression in error rates, but not RTs ($F(1, 17) = 7.51, p = .01$; $F(1, 17) = 1.32, p = .27$). Subjects were more error prone in the AS condition ($M = 6\%$) relative to the standard condition ($M = 4\%$). As expected, there was a significant block x CSI interaction in both RTs and errors ($F(1, 17) = 5.62, p = .03$; $F(1, 17) = 5.32, p = .03$), as switch costs decreased significantly from the 250 CSI to the 650 CSI (*M* decrease = 39 ms, 3%; $t(18) = -2.45, p = .02$ for the RT decrease, $t(18) = 2.38, p = .03$ for the error decrease). As predicted, there was no two-way suppression x block interaction (both *p*'s > .30): switch costs in the AS condition ($M = 110$ ms, 3%) did not differ from costs in the standard condition ($M = 105$ ms, 2%). However, the suppression x block x test order interaction approached significance for RTs ($F(1, 17) = 4.19, p = .06$). When subjects completed the AS condition before the standard condition, switch costs were larger in the AS condition ($M = 106$ ms) relative to the standard condition ($M = 67$ ms), though not significantly so ($t(8) = -1.29, p = .23$). In contrast, when subjects completed the standard condition before the AS condition, switch costs in the standard condition ($M = 121$ ms) were larger than those in the AS condition ($M = 94$ ms), though again this difference was not significant ($t(9) = 1.95, p = .08$). In errors, none of the interactions with test order reached significance. Lastly, as in Experiment 2, the three-way suppression x block x CSI interaction approached significance RTs, but not errors

($F(1, 17) = 4.24, p = .06$; $F(1, 17) = 0.03, p = .88$). As can be seen in Figure 9B, there was an obvious switch cost decrease in the standard condition, from the 250 to 650 CSI (*M* decrease = 67 ms) but no such decrease in the AS condition (*M* decrease = 10 ms).

Figure 9. Global task switching effects for controls in Experiment 3. Figure 9A (left): mean RTs by block (mixed, pure) and CSI (250, 650). Figure 9B (right, top): mean global switch costs by CSI. For top figures, error bars depict standard error of the mean. Figure 9B (right, bottom): box plots displaying control switch cost distributions, including minimum and maximum (whiskers), quartiles (box), and median (single line).

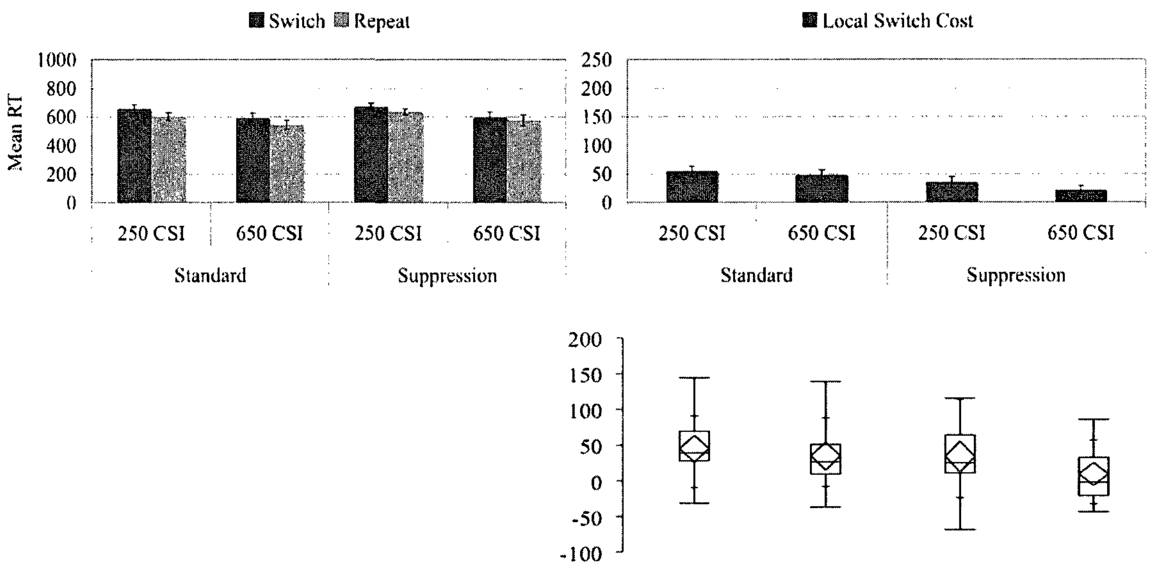


Another way to assess the effect of WM load on task switching is to make cross-experiment comparisons, given that Experiment 3 (partial cueing) was designed as a slightly higher WM load version of Experiment 2 (full cueing). For controls, cross-experiment comparisons were made using a repeated-measures ANOVA with experiment (full cueing, partial cueing), suppression (standard, AS), block (mixed, pure) or trial type (switch, repeat), and CSI (250, 650) as within-subject factors. For the present purposes, we are only interested in the effects involving the experiment factor.

Comparing the global switch costs (mixed and pure blocks) in the full and partial cueing condition results in a main effect of experiment ($F(1, 18) = 14.19, p = .001$), as overall RTs in the full cueing experiment ($M = 613$ ms) were significantly slower than RTs in the partial cueing experiment ($M = 545$ ms). There was also a significant experiment x block interaction ($F(1, 18) = 14.76, p = .001$), as global switch costs in the full cueing experiment ($M = 170$ ms) were significantly greater than global switch costs in the partial cueing experiment ($M = 97$ ms), $F(1, 18) = 15.57, p < .001$. Given Experiment 3 – the partial cueing condition – was predicted to have little to no effect on global switch costs, these results might seem surprising at first. If anything, the higher WM load in the partial cueing condition should cause slower times in the partial cueing experiment (opposite of what was found). However, it is very possible that these switch cost reductions across experiments result from practice effects. Although controls were given practice trials prior to each testing session, their performance still improved from Experiment 2 to Experiment 3. But, as patients also participated in all experiments, in the same order, these practice effects are not of much concern. More importantly, none of the other interactions with experiment were significant (all p's $< .05$), suggesting similar suppression and switch cost effects across the two cueing experiments. As expected, the WM load added in the partial cueing experiment had no effect on controls' global switch costs.

Controls: Local switch costs. Figure 10A displays mean response times for repeat and switch trials, across CSIs for the standard and AS conditions; the difference between these switch and repeat blocks is the local switch cost. Subjects were highly accurate across conditions (M error = 6%). There was no main effect of test order in either RTs or errors (both p's > .45). There was a significant main effect of trial type in both RT and error rates ($F(1, 17) = 29.26$, $p < .001$; $F(1, 17) = 25.67$, $p < .001$): subjects were slower and more error prone on switch trials ($M = 628$ ms, 9%) relative to repeat trials ($M = 589$ ms, 5%). While there was no main effect of suppression in RT analyses ($F(1, 17) = 1.86$, $p = .19$), this main effect was significant in error analyses ($F(1, 17) = 6.64$, $p = .02$) – in general, subjects were slower and more error prone in the AS condition ($M = 618$ ms, 8%) relative to the standard condition ($M = 598$ ms, 5%). There was a significant trial type x CSI interaction in RTs ($F(1, 17) = 6.83$, $p = .02$), but not errors ($F(1, 17) = 0.11$, $p = .75$). RT switch costs significantly decreased from the 250 CSI to the 650 CSI (M decrease = 12 ms; $t(18) = -2.75$, $p = .01$). Again, importantly, there was no two-way interaction between suppression and trial type in either RT or error rates ($F(1, 17) = 3.17$, $p = .09$; $F(1, 17) = 0.15$, $p = .70$): while subjects were slower and more error prone in the AS condition overall, switch costs in the AS condition ($M = 28$ ms, 4%) did not differ from costs in the standard condition ($M = 50$ ms, 3%). There was again a three-way suppression x block x test order interaction in RTs ($F(1, 17) = 4.41$, $p = .05$). When subjects completed the AS condition before the standard condition, switch costs were larger in the AS condition ($M = 106$ ms) relative to the standard condition ($M = 67$ ms), though this difference was not significant ($t(8) = -0.30$, $p = .77$). In contrast, when subjects completed the standard condition before the AS condition, switch costs were significantly larger in the standard condition ($M = 121$ ms) relative to the AS condition ($M = 94$ ms; $t(9) = 2.71$, $p = .02$. In errors, none of the interactions with test order reached significance. Lastly, the three-way suppression x trial type x CSI interaction was also not significant in RTs or errors ($F(1, 18) = 2.47$, $p = .13$; $F(1, 18) = 0.32$, $p = .58$). As can be seen in Figure 10B, switch costs in both the AS and standard conditions decreased as a function of CSI.

Figure 10. Local task switching effects for controls in Experiment 3. Figure 10A (left): mean RT by block (mixed, pure) and CSI (250, 650). Figure 10B (right, top): mean proportional local switch costs by CSI. For top figures, error bars depict standard error of the mean. Figure 10B (right, bottom): box plots displaying control switch cost distributions, including minimum and maximum (whiskers), quartiles (box), and median (single line).



For controls, local switch cost (mixed block only: switch and repeat trials) cross-experiment comparisons were similar to the findings from global costs. For the full vs. partial cueing condition, there was a main effect of experiment ($F(1, 18) = 14.61$, $p = .001$), as RTs in Experiment 2 ($M = 700$ ms) were significantly slower than RTs in Experiment 3 ($M = 595$ ms). No other interactions with the experiment factor were significant (all p's > .05), suggesting similar cross-experiment suppression and local switch cost effects in the full and partial cueing conditions, despite differences in overall response speed. Again as expected, the WM load differences associated with partial cueing, relative to full cueing, had no effect on controls.

Patients: global switch costs. Comparisons of patient and control proportional global switch costs are shown in Figure 11A. Given that both global and local switch costs for controls under AS were numerically smaller than costs in the standard condition, we only compared costs to control costs in the standard condition. Patient proportional global switch costs and associated t-test statistics are shown in Table 8. Four of the seven patients (BB, BQ, EV, MB) showed significantly greater switch costs across both CSIs, while the remaining three patients (ML, SH, SJ) showed switch costs that did not differ from controls. As can be seen in Figure 11A, individual patient switch costs across CSI tended to be greater than the costs shown by controls. However, all of the patients except for EV did show a switch cost decrease as a function of the CSI. Again, some patients showed a very large benefit of CSI increase (e.g. patients BB, BQ, ML).

Figure 11. Task switching effects for controls (in standard (Std.) and suppression (Supp.) conditions) and patients in Experiment 3. Figure 11A (top): proportional global switch cost by CSI (250, 650). Figure 11B (bottom): proportional local switch cost by CSI. Error bars show minimum and maximum for controls and tick marks show standard deviations.

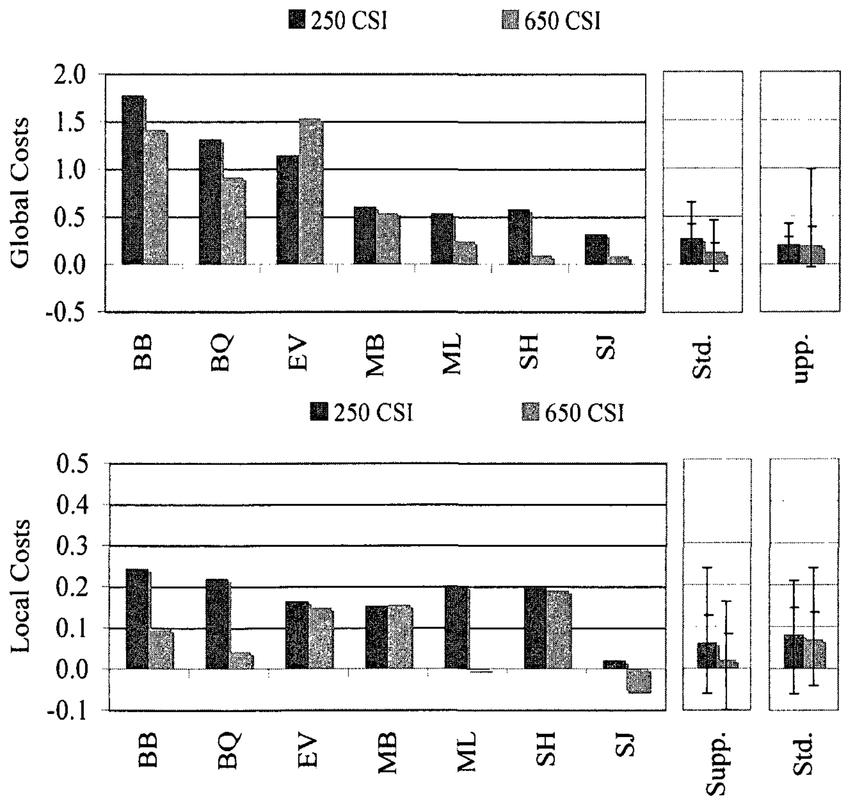


Table 8. Proportional global switch costs and t-test statistics for patients, along with the mean and standard deviation (in parentheses) for controls in the standard and AS conditions in Experiment 3. Asterisks indicate patient switch costs that differ significantly from controls.

	250 CSI			*650 CSI*		
	M	*t*	*P*	*M*	*t*	*p*
BB	1.77	9.76	<.001*	1.41	9.60	<.001*
BQ	1.31	6.77	<.001*	0.91	5.84	<.001*
EV	1.14	5.66	<.001*	1.53	10.50	<.001*
MB	0.60	2.17	.04*	0.54	3.04	.007*
ML	0.53	1.67	.11	0.24	0.80	.43
SH	0.58	1.99	.06	0.09	-0.29	.78
SJ	0.31	0.28	.78	0.08	-0.34	.74
Controls, standard	0.27 (.15)			0.13 (.13)		
Controls, suppression	0.20 (.12)			0.19 (.23)		

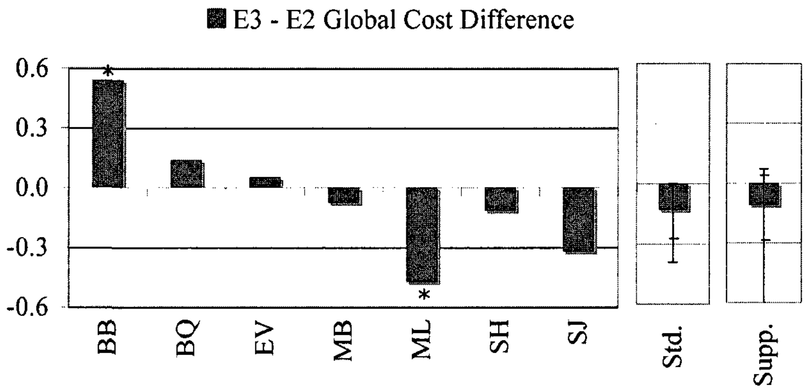
Although the patients tended to be slower than controls, most patients made very few errors in this task switching paradigm. Global switch costs, calculated as the difference in errors between mixed and pure blocks, are shown in Table 9. However, two patients had error rates that were significantly larger than controls, as confirmed by individual t-tests on the mixed, pure, and switch cost errors – BQ showed significantly more errors in the mixed block (but not the pure block), resulting in a switch cost that was significantly larger than controls. EV, on the other hand, make significantly more errors in both the mixed and pure blocks – given this, her actual switch cost was in the normal range. Given that all patient error rates were within the range of controls for Experiment 2, this increase in error rates can be attributed to the only design change between Experiments 2 and 3: the need to retain the cue once the target appeared. The remaining patients made very few errors.

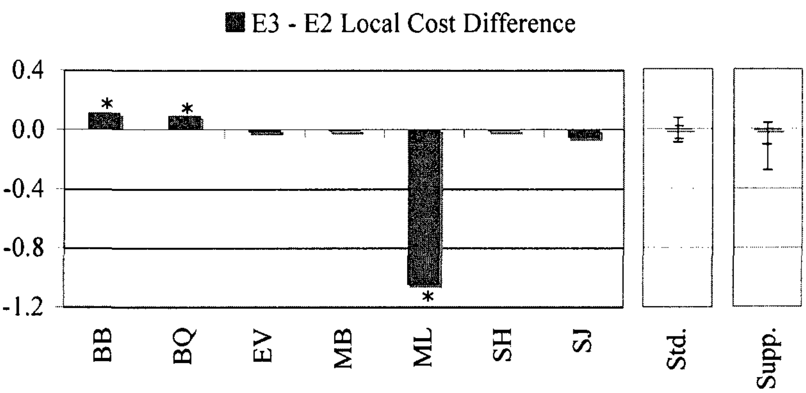
Table 9. Error rates for global and local switch costs for patients, along with the mean and standard deviation for controls in the standard and AS conditions in Experiment 3. Asterisks indicate patient switch costs that differ significantly from controls.

	Global			*Local*		
	Mixed Block	Pure Blocks	Switch Cost	Switch Trials	Repeat Trials	Switch Cost
BB	0.04	0.02	0.02	0.05	0.04	0.01
BQ	0.14*	0.02	0.12*	0.18*	0.10*	0.08
EV	0.20*	0.21*	0.00	0.19*	0.22*	-0.03
MB	0.03	0.01	0.02	0.05	0.01	0.05
ML	0.03	0.02	0.02	0.04	0.02	0.02
SH	0.00	0.00	0.00	0.00	0.01	-0.01
SJ	0.04	0.01	0.03	0.02	0.05	-0.02
Controls, standard (SD)	0.05 (0.03)	0.03 (0.03)	0.02 (.02)	0.07 (0.05)	0.03 (0.03)	0.04 (0.04)
Controls, suppression, (SD)	0.07 (.05)	0.04 (.05)	0.03 (.03)	0.09 (.05)	0.06 (.06)	0.03 (.03)

For patients, cross-experiment global switch cost comparisons were made by looking at the difference between proportional global switch costs (averaged over CSI) in the partial cueing condition (Experiment 3) and the full cueing condition (Experiment 2). Mean and standard deviations of this difference score were also calculated for controls, in order to calculate whether patient cross-experiment switch cost differences differed from controls (Crawford & Howell, 1998). Given controls had smaller switch costs in the present Experiment relative to Experiment 2, we are proposing that negative differences represent switch costs changes resulting from practice (like controls, as described above) whereas positive differences represent effects related to cue processing (as this was the only Experiment 2-3 design difference). As can be seen in Figure 12A (top), only patient ML showed practice effects that were significantly larger than controls. In contrast, only patient BB showed significant switch cost increases across experiments, indicating that he was differentially affected by the full and partial cueing condition. All other patient global switch cost changes were within the range of controls.

Figure 12. Proportional cross-experiment switch cost changes, measured as the difference between partial cueing (Experiment 3) and full cueing (Experiment 2) conditions. Figure 12A (top): global switch cost changes. Figure 12B (bottom): local switch cost changes. Asterisks indicate patient values that differ significantly from controls.





Patients: local switch costs. Comparison of patient and control proportional local switch costs can be seen in Figure 11B (above), with costs and associated t-test statistics are shown in Table 10, with the standard control condition serving as the patient comparison. Of the seven patients, only patient BQ showed a significantly larger switch cost, and only at the 250 CSI. Otherwise, the remaining six patients showed switch costs within the range of controls. As can be seen in Figure 11B, patients still tended to have longer switch costs overall, but there is still a general pattern of decreased switch cost as a function of increased CSI. Again, several patients (BB, BQ, ML) showed large benefits of increased CSI.

Table 10. Proportional local switch costs and t-test statistics for patients, along with means and standard deviations (in parentheses) for controls in the standard and AS conditions in Experiment 3. Asterisk indicates patient switch cost that differs significantly from controls.

	250 CSI			*650 CSI*		
	M	*t*	*p*	*M*	*t*	*p*
BB	0.24	2.26	.04*	0.10	0.35	.73
BQ	0.22	1.93	.07	0.04	-0.40	.69
EV	0.16	1.16	.26	0.15	1.08	.29
MB	0.15	1.00	.33	0.15	1.18	.25
ML	0.20	1.68	.11	0.00	-1.01	.33
SH	0.20	1.61	.12	0.19	1.67	.11
SJ	0.02	-0.83	.42	-0.05	-1.71	.10
Controls, standard	0.08 (.07)			0.07 (.07)		
Controls, suppression	0.06 (.07)			0.02 (.07)		

Local switch costs, calculated as the difference in errors between switch and repeat trials averaged across CSI, are shown in Table 9 (above). Although patients tended to be slower than controls, five of the seven made very few errors in this local task switching paradigm. Only two patients had error rates that were significantly larger than controls, as confirmed by individual t-tests on the mixed, pure, and switch cost errors – both BQ and EV showed significantly more errors in both the mixed and pure blocks. However, because they made more errors in both blocks, their actual switch costs were in the normal range. The remaining patients made very few errors.

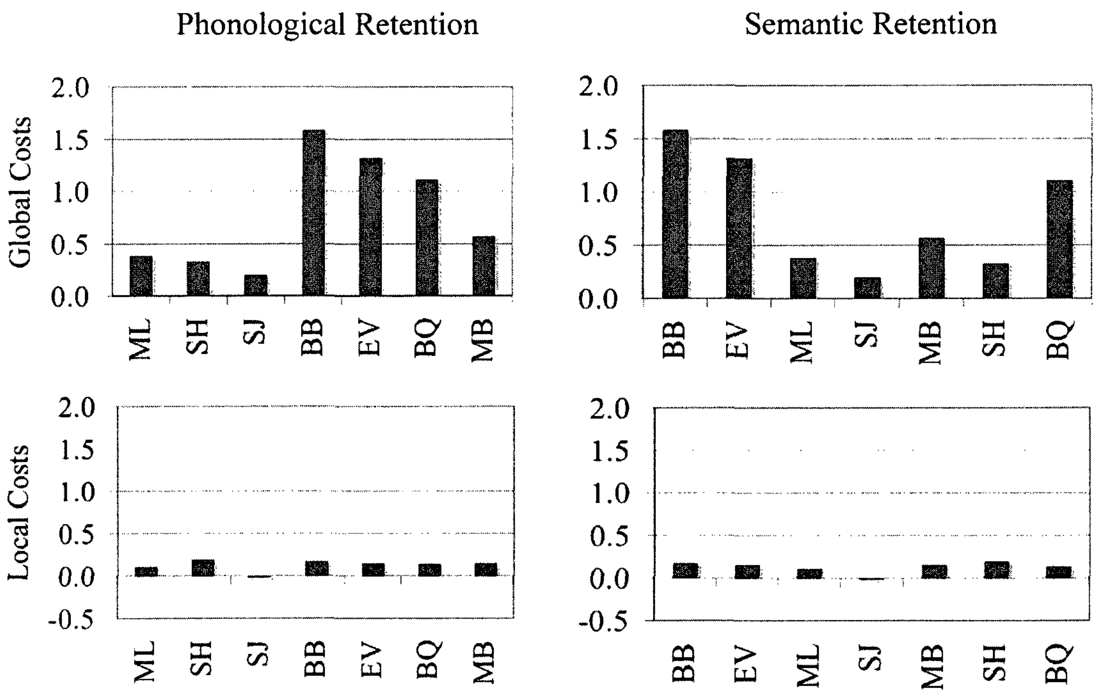
Cross-experiment local switch cost comparisons were made by looking at the difference between proportional local switch costs (averaged over CSI) in the partial cueing condition (Experiment 3) and the full cueing condition (Experiment 2). In local effects, controls showed no switch cost change as a function of experiment. As can be seen in the bottom of Figure 12B (above), only patient ML showed significantly smaller local costs in Experiment 3, relative to Experiment 2. In contrast, patients BB and BQ both showed significant switch cost increases across experiments, indicating that they may have been differentially affected by the full and partial cueing conditions, above and beyond exaggerated switch costs. All other patient local switch cost changes were within the range of controls.

Relationship between switch costs and short-term retention. We again examined the relationship between switch costs and short-term retention. Did the WM load increase in the shifting paradigm result in a relationship between shifting and short-term retention? If so, for phonological or semantic retention? Relationships were examined in the manner as Experiment 2.

Global switch costs for controls correlated with neither the rhyme probe ($r = -.22$, $p = .36$) nor the category probe ($r = .11$, $p = .66$), suggesting switch costs in this low WM load condition are not related to short-term retention. Additionally, neither measure made significant, independent contributions to switch cost prediction (both p's > .25). Additionally, as seen in Figure 13A (top), patient global switch costs had no obvious relationship with phonological retention. In contrast, it appears the two patients (BB, EV) with the lowest semantic spans did show the largest switch costs, though patient BQ, with the largest semantic span, also had a large switch costs relative to other patients. Therefore, it is not clear that there is a relationship between global costs and semantic retention in this experiment.

Likewise, local switch costs for controls correlated with neither rhyme probe (r = .26, p = .28) nor category probe (r = .25, p = .31). Again, neither measure made significant, independent contributions to switch cost prediction (both p's > .50). Patient span relationships with local costs are shown in Figure 13B (bottom). For local costs, there was clearly no obvious relationship between switch costs and either phonological or semantic retention.

Figure 13. Relationship between switch costs and short-term retention for patients in Experiment 3. Figure 13A (top): Patient global switch costs as a function of phonological (left) and semantic (right) retention. Figure 13B (bottom): local switch costs as a function of phonological (left) and semantic (right) retention.



Experiment 3 Discussion

Experiment 3 utilized a partial cueing condition in which the cue was a word that only remained on the screen throughout the duration of the CSI. Successful task performance in this condition requires subjects maintain task set information once the cue disappears. Despite the slightly increased WM demand of this task, we predicted little to no cue manipulation effect on controls, which is what was found. Looking at the control data, the results of Experiment 3 were generally in line with predictions, and essentially identical to Experiment 2. Neither global nor local switch costs interacted with suppression, suggesting that shifting was not affected by AS (Baddeley et al., 2001; Miyake et al., 2004). In fact, again, switch costs in the AS condition tended to be smaller than those in the standard condition. This finding supports the notion that for neurologically healthy individuals, phonological processes such as inner speech are not important when task sets are explicitly activated, even if cue information must be retained for a short duration. Supporting this notion, switch costs did not correlate with measures of short-term retention.

Like Experiment 2, global (but not local) switch costs differed as a function of suppression and CSI, such that global switch costs in the AS condition did not show a well-replicated reduction as a function of increased CSI, though this reduction was found in the standard condition. This will be further discussed in the General Discussion.

The comparison of full vs. partial cueing conditions demonstrate faster RTs in the partial cueing condition, relative to the full cueing condition in global switch costs. Given the partial cueing experiment was designed to increase the WM load of the shifting task, these results are counterintuitive at first glance. However, these RT decreases most likely result from practice effects. Although subjects received multiple practice sessions, it is possible that learning transferred over testing sessions, making subjects faster overall in Experiment 3. Additionally, although subjects' local RTs were faster overall, there was no change in local switch cost as a function of the cueing condition. More importantly, suppression did not differentially affect switch costs across Experiments 2 and 3, allowing us to safely conclude that the partial cueing condition did not differentially affect shifting ability, as predicted.

We expected patients, unlike controls, to be affected by the increase WM demands associated with the partial cueing condition. Like Experiment 2, patients BB, BQ and EV showed significantly greater global switch costs than controls. In addition to these three patients, MB also showed significantly greater switch costs in both CSIs. Additionally, patients BQ and EV made significantly more errors than controls, unlike Experiment 2. In the cross-experiment comparisons, only patient BB showed increased switch costs as a function of cue processing requirements. That is, unlike controls, some patients' (BB, BQ, EV, and MB) global shifting measures were clearly affected by the cue retention manipulation of Experiment 3. However, patient costs were not obviously related to either phonological or semantic retention.

With local switch costs, only patient BB showed greater costs than controls, and only in a single CSI. Additionally, patients BB and BQ's local switch costs were significantly increased from Experiment 2 to Experiment 3, as a function of cue processing demands. Thus, it seems that some patients were, in fact, affected by the increased cue processing demands associated with partial cueing, unlike controls. Again, however, there was no obvious relationship between local costs and measures of short-term retention. The partial cueing experiment also affected patient error rates differently than Experiment 2. In Experiment 2, the full cueing condition, patients made minimal errors, all within the range of controls. In the present, partial cueing experiment, however, two patients – BQ and EV – made significantly more errors than controls. Given the cue duration was the only design difference between the two experiments, these difference again support the notion that the slight WM load modification (partial cueing) affected patient performance to some degree, though some patients were affected more than others.

Experiment 4

Overview and predictions

With the exception of the type of cue, the design of Experiment 4 is identical to Experiment 2. In Experiment 4, the cue was presented throughout the duration of the trial, but it was a symbol, rather than an explicit word (as in Experiments 1-3). '%%%%%' represented the 'Shape' task and '&&&&&' represented the color task. This full symbolic cueing experiment required additional cue processing because the symbol must first be interpreted before it can be utilized to determine the task set relevant to a given trial. Thus, this cue processing is predicted to evoke additional short-term memory resources, instantiated as increased switch costs in controls, relative to the full cueing condition (Experiment 2). Additionally, for controls, these cue processing demands were predicted to be moderately low in the standard condition, given that task set changes in the mixed blocks are predictable (AABBAA). Under standard conditions, controls could potentially utilize the predictability of switches to maintain task order (color, color, shape, shape) using subvocal rehearsal. In contrast, the cue processing demands were predicted to be much greater under AS. Under AS, controls would be unable to use phonological rehearsal as effectively, resulting in performance decrements. Importantly, we also predicted a detrimental effect of cue processing for the STM patients.

Participants

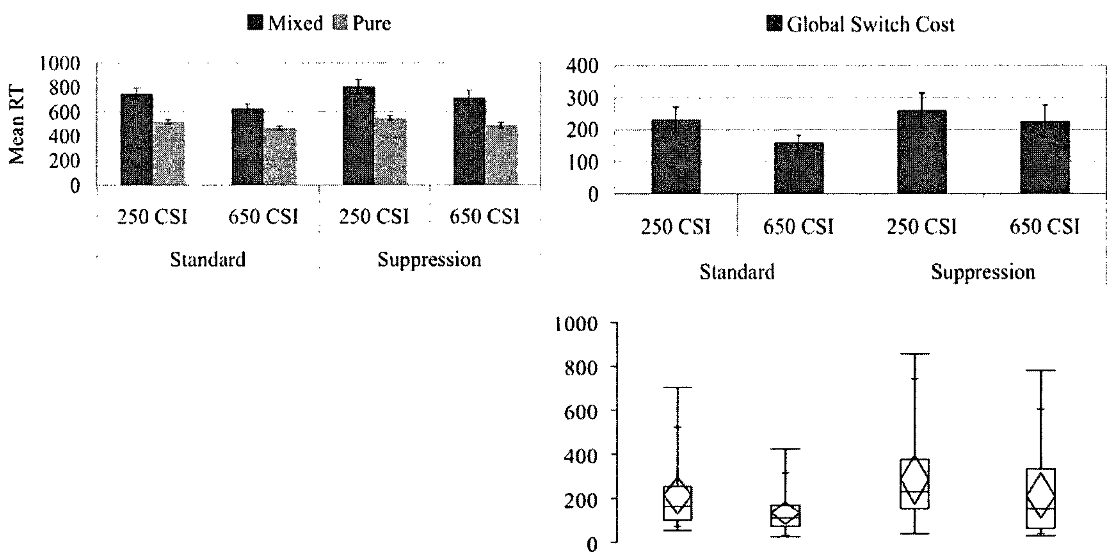
18 of the same, previously tested control subjects participated in Experiment 4; one control subject was unable to return for the final testing sessions. Additionally, only six patients participated in Experiment 4. During practice, patient BB expressed difficulty with the symbolic cueing condition and was unable to proceed; this will be further discussed below.

Results

Controls: Global switch costs. Figure 14A displays mean response times for mixed and pure blocks, across CSIs for the standard and AS conditions; the difference between these mixed and pure blocks is the global switch cost. On average, subjects were again highly accurate across all conditions (M error = 5%). There were no main effects of or interactions involving test order in RTs or errors. As such, this between-subjects variable will not be discussed further. As expected, there was a main effect of block in both RTs and errors ($F(1, 16) = 28.17, p < .001$; $F(1, 16) = 12.82, p = .002$), as subjects were slower and more error prone in mixed blocks (M = 722 ms, 9%) relative to pure blocks (M = 505 ms, 3%). There was a main effect of suppression in RTs ($F(1, 16) = 9.66, p = .007$), but not errors ($F(1, 16) = 0.97, p = .34$); subjects were slower in the AS condition (M = 637 ms) relative to the standard condition (M = 581 ms). There was also a significant block x CSI interaction in both RTs and errors ($F(1, 16) = 6.04, p = .03$; $F(1, 16) = 11.21, p = .004$), as switch costs decreased from the 250 CSI to the 650 CSI (M decrease = 55 ms, 5%; RT decrease: $t(17) = -2.52, p = .02$; error decrease: $t(17) = -3.47, p = .003$). Importantly, as predicted, there *was* a two-way suppression x block interaction (unlike in Experiments 2 and 3) in RT ($F(1, 16) = 6.82, p = .02$), but not error rates (F(1,

16) = 0.52, p = .48): switch costs in the AS condition (M = 244 ms) were significantly greater than switch costs in the standard condition (M = 192 ms), $t(17) = -2.39$, p = .03. The three-way suppression x block x CSI interaction was not significant in RT or errors (both p's > .35). As can be seen in Figure 14B, there was a significant RT switch cost decrease in both the standard (M decrease = 72 ms) and AS conditions (M decrease = 35 ms).

Figure 14. Global task switching effects for controls in Experiment 4. Figure 14A (left): mean RT by block (mixed, pure) and CSI (250, 650). Figure 14B (right, top): mean global switch costs by CSI. For top figures, error bars depict standard error of the mean. Figure 14B (right, bottom): box plots displaying control switch cost distributions, including minimum and maximum (whiskers), quartiles (box), and median (single line).

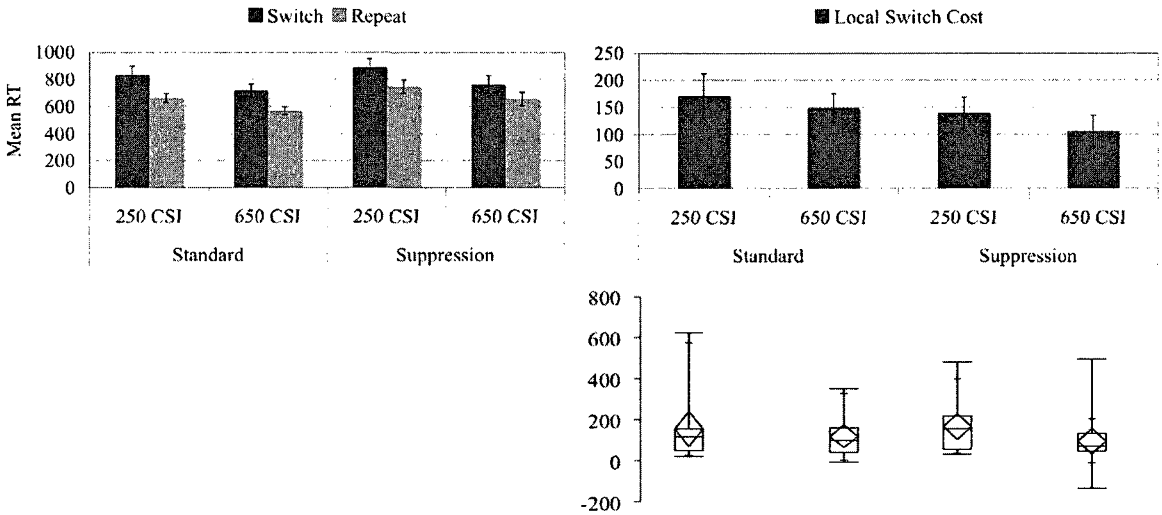


One final test of the effect of WM load on task switching is the comparison of cross-experiment effects, comparing the full cueing experiment (Experiment 2) to the full symbolic cueing experiment (present Experiment). For controls, we predicted that the increased WM load would be most detrimental in the AS condition, when phonological resources are unavailable to keep track of the current task set. Importantly, we also predicted a detrimental effect of cue processing for the STM patients. To assess these effects in controls, a within-subjects ANOVA was run with experiment (full cueing, symbolic cueing), suppression (standard, AS), block (mixed, pure) or trial type (switch, repeat), and CSI (250, 650) as within-subject factors. For the present purposes, we are only interested in the main effects and interactions involving the experiment factor.

For the global switch costs measures (mixed and pure blocks), comparing the full and symbolic cueing conditions, there was no main effect of experiment ($F(1, 17) = 2.35$, $p = .14$), as overall RTs in Experiment 2 ($M = 613$ ms) were statistically similar to the RTs in Experiment 4 ($M = 589$ ms). Additionally, only the experiment x suppression x block interaction was significant ($F(1, 17) = 4.69$, $p = .05$). As predicted, symbolic cueing was specifically detrimental in the AS condition ($M = 230$ ms), as these costs were significantly greater than switch costs in the symbolically cued standard condition ($M = 152$ ms; $F(1, 17) = 5.71$, $p = .03$). Switch costs in this symbolically cued standard condition were not statistically different from switch costs in the full cueing standard ($M = 167$ ms) or AS ($M = 165$ ms) conditions; $F(1, 17) = 1.15$, $p = .30$). Thus, as found in previous research, AS had different effects on global switch costs, depending on the type of cue (Emerson & Miyake, 2003) and the requirement for endogenous control (Bryck & Mayr, 2005; Rogers & Monsell, 1995). Counter to Emerson and Miyake (2003), cue difficulty did not affect switch costs in the standard condition; however, unlike the present experiment, Emerson and Miyake used random cueing, such that task switches were not predictable. The predictability of the present experiment hypothetically allows subjects to keep track of the current task set using phonological processes, rather than symbolic cue interpretation. This hypothesis is supported by the fact that the symbolic cue condition was the only global cost affected by AS – when phonological processes were removed, shifting suffered.

Controls: Local switch costs. Figure 15A displays mean response times for repeat and switch trials, across CSIs for the standard and AS conditions; the difference between these switch and repeat blocks is the local switch cost. Subjects were relatively accurate across conditions (*M* error = 7%). There were no main effects of or interactions involving test order in RTs or errors. As such, this between-subjects variable will not be discussed further. There was a main effect of trial type in both RTs and errors ($F(1, 16) = 25.24, p < .001$; $F(1, 16) = 15.18, p = .001$), as subjects were slower and more error prone on switch trials ($M = 800$ ms, 11%) relative to repeat trials ($M = 656$ ms, 7%). The main effect of suppression was significant in RT analyses ($F(1, 16) = 9.17, p = .008$), but not error analyses ($F(1, 16) = 0.05, p = .83$). In general, subjects were slower in the AS condition ($M = 762$ ms) relative to the standard condition ($M = 691$ ms). There was also a significant trial type type x CSI interaction in RTs but not errors ($F(1, 16) = 4.66, p = .05$; $F(1, 16) = 2.28, p = .15$). Switch costs significantly decreased from the 250 CSI to the 650 CSI (*M* decrease = 32 ms; $t(17) = -2.10, p = .05$). There was no interaction between suppression and trial type in either RTs or error rates (both p's > .30): while subjects were slower and more error prone in the AS condition overall, switch costs in the AS condition ($M = 126$ ms, 4%) did not differ from costs in the standard condition ($M = 159$ ms, 3%). Lastly, the three-way suppression x trial type x CSI interaction was also not significant in RTs or errors (both p's > .25). As can be seen in Figure 15B, switch costs in both the AS and standard conditions decreased as a function of CSI.

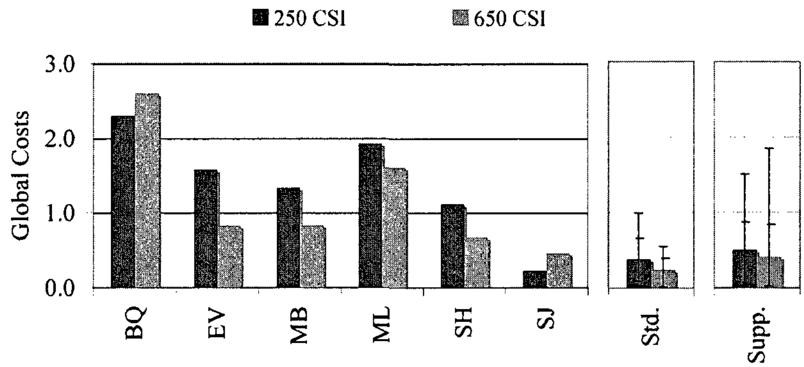
Figure 15. Local task switching effects for controls in Experiment 4. Figure 15A (left): mean RT by block (mixed, pure) and CSI (250, 650). Figure 15B (right, top): mean proportional local switch costs by CSI. For top figures, error bars depict standard error of the mean. Figure 15B (right, bottom): box plots displaying control switch cost distributions, including minimum and maximum (whiskers), quartiles (box), and median (single line).



For cross-experiment effects on local switch cost measures (mixed block only: switch and repeat trials), comparing full and symbolic cueing conditions, there was no main effect of experiment ($F(1, 17) = 0.07, p = .80$), but there was a significant experiment x trial type interaction ($F(1, 17) = 14.15, p = .002$) as local switch costs in the full cueing condition ($M = 44$ ms) were significantly smaller than those in the symbolic cueing condition ($M = 116$ ms). Given there were no RT differences between the standard and AS conditions, in either the full or symbolic cueing conditions, it is unsurprising to find that the experiment x suppression x trial type interaction was not significant ($F(1, 17) = 0.06$, $p = .80$). Although local switch costs in the fully cued experiment were faster overall, AS did not have differential effects on these switch costs across experiments. These findings are inline with other studies that have found no local switch cost changes under suppression conditions (e.g. Bryck & Mayr, 2005; Saeki & Saito, 2004b).

Patients: global switch costs. Comparisons of patient and control proportional global switch costs are shown in Figure 16A, with costs and associated t-test statistics are shown in Table 11. Given that global switch costs for controls under AS were significantly larger than costs in the standard condition, we compared patient costs to controls in the both the standard and AS conditions to determine if the patients were more like controls under AS. As expected, the full symbolic cue had a detrimental effect on patient performance. Five of the six patients (with the exception of SJ) showed significantly larger switch costs across both CSIs, and one patient (BB) refused to complete this experiment due to task difficulty. As can be seen in Figure 16A, individual patient switch costs across CSI tended to be greater than the costs shown by controls. However, patient performance looks better when compared to controls under AS. Specifically, under these conditions, only three patients show costs that are greater than controls under AS at the 250 CSI (BQ, EV, ML), with only two patients continuing to show exaggerated costs at the 650 CSI (BQ, ML). Lastly, most of the patients did show a switch cost decrease as a function of the CSI. Again, some patients showed a very large benefit of CSI increase (e.g. patients EV, MB, ML, SH).

Figure 16. Task switching effects for controls (in standard (Std.) and suppression (Supp.) conditions) and patients in Experiment 4. Figure 16A (top): proportional global switch cost by CSI (250, 650). Figure 16B (bottom): proportional local switch cost by CSI. Error bars show minimum and maximum for controls and tick marks show standard deviations.



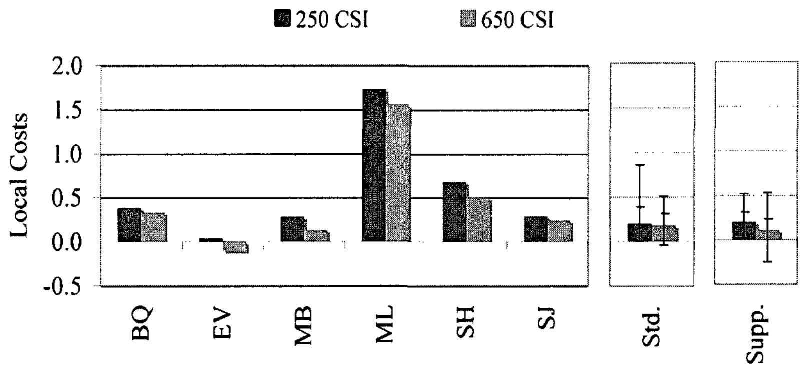


Table 11. Proportional global switch costs and t-test statistics for patients, along with the mean and standard deviation (in parentheses) for controls in the standard and AS conditions in Experiment 4. Comparisons (t and p values) for both the standard (top of a cell) and AS (bottom of a cell) conditions are shown. Asterisks indicate patient switch costs that differ significantly from controls.

	250 CSI			*650 CSI*		
	M	*t*	*p*	*M*	*t*	*p*
BQ	2.30	6.45 4.28	<.001* <.001*	2.60	12.77 4.54	<.001* <.001*
EV	1.58	4.03 2.56	<.001* .02*	0.83	3.17 0.86	.006* .40
MB	1.33	3.19 1.97	.005* .07	0.83	3.20 0.87	.005* .40
ML	1.92	5.18 3.38	<.001* .004*	1.61	7.41 2.49	<.001* .02*
SH	1.11	2.47 1.46	.02* .16	0.67	2.32 0.54	.03* .60
SJ	0.22	-0.52 -0.66	.61 .52	0.46	1.19 0.10	.25 .92
Controls, standard	0.38 (.29)			0.24 (.18)		
Controls, suppression	0.50 (.41)			0.41 (.47)		

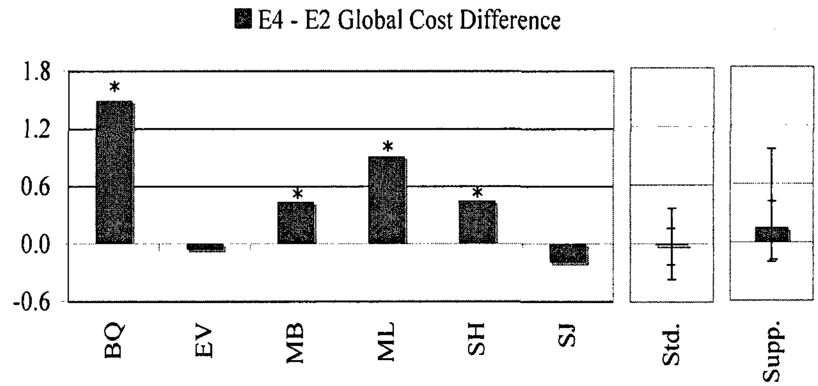
Although the patients tended to be slower than controls, most patients made very few errors in this task switching paradigm, even with the increased memory load. Global switch costs, calculated as the difference in errors between mixed and pure blocks, are shown in Table 12. Only patient ML had a switch costs that was significantly larger than controls, due to his poor performance in the mixed blocks (though not significantly different than controls), but good performance in the pure blocks. Similarly, although patient BQ's switch cost is larger than the mean for controls, it does not differ significantly from controls. As with previous experiments, the remaining patients made very few errors.

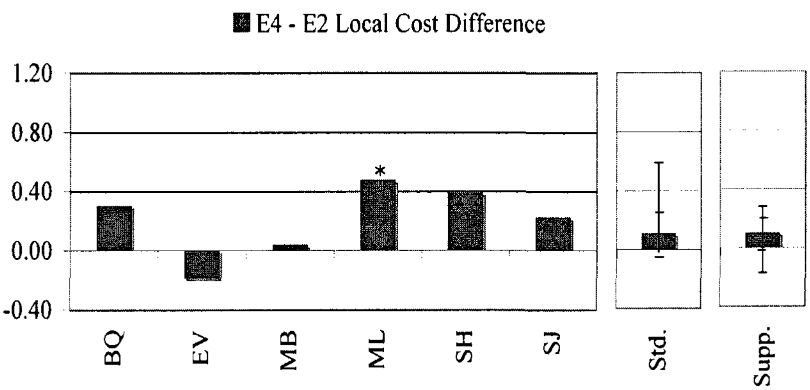
Table 12. Error rates for global and local switch costs for patients, along with the mean and standard deviation (in parentheses) for controls in the standard and AS conditions in Experiment 4. Asterisk indicates patient switch cost that differs significantly from controls.

	Global			*Local*		
	Mixed Block	Pure Blocks	Switch Cost	Switch Trials	Repeat Trials	Switch Cost
BQ	0.16	0.01	0.16	0.18	0.15	0.03
EV	0.02	0.01	0.02	0.02	0.02	0.00
MB	0.01	0.00	0.00	0.02	0.00	0.02
ML	0.21	0.01	0.20*	0.21	0.20	0.01
SH	0.01	0.00	0.01	0.01	0.01	0.00
SJ	0.02	0.00	0.01	0.03	0.00	0.03
Controls, standard	0.07 (0.09)	0.02 (0.02)	0.05 (.07)	0.09 (0.09)	0.06 (0.08)	0.03 (0.04)
Controls, suppression	0.07 (.07)	0.03 (.04)	0.04 (.04)	0.09 (.07)	0.06 (.07)	0.04 (.04)

For patients, cross-experiment global switch cost comparisons were made in the same way as Experiment 3: by looking at the difference between proportional global switch costs (averaged over CSI) in the symbolic cueing condition (Experiment 4) and the full cueing condition (Experiment 2). As can be seen in Figure 17A (top), four of the six patients tested on the symbolic cueing condition showed greater cue processing effects than controls – that is, as predicted, these four patients were more detrimentally effected by symbolic cues (relative to full cues) than controls.

Figure 17. Proportional cross-experiment switch cost changes, measured as the difference between symbolic cueing (Experiment 4) and full cueing (Experiment 2). Figure 17A (top): global switch cost changes. Figure 17B (bottom): local switch cost changes. Asterisks indicate patient values that differ significantly from controls.





Patients: local switch costs. Comparison of patient and control proportional local switch costs can be seen in Figure 16B (above), with costs and associated t-test statistics are shown in Table 13, with the standard control condition serving as the patient comparison. Given that local switch costs for controls under AS were numerically smaller than costs in the standard condition, we only compared patients to control costs in the standard condition. Of the six patients, only patient ML showed significantly larger switch costs at both CSIs, and only patient SH showed a significantly greater switch cost at a single CSI. That is, unlike their global switch costs, which tended to suffer from the symbolic processing aspect of the task, local switch costs were relatively unimpaired. Aside from ML and SH, the remaining four patients showed local switch costs within the range of controls. As can be seen in Figure 17B, cross-experiment (Experiments 2 and 4) changes in local switch costs were not greatly exaggerated. Also, overall, all patients show a pattern of decreased switch cost as a function of increased CSI.

Table 13. Proportional local switch costs and t-test statistics for patients, along with the mean and standard deviation (in parentheses) for controls in the standard and AS conditions in Experiment 4. Asterisks indicate patient switch costs that differ significantly from controls.

	250 CSI			*650 CSI*		
	M	*t*	*p*	*M*	*t*	*p*
BQ	0.38	0.84	.41	0.33	0.87	.40
EV	0.04	-0.76	.23	-0.11	-1.63	.12
MB	0.28	0.37	.72	0.13	-0.30	.77
ML	1.73	7.08	<.001*	1.56	7.88	<.001*
SH	0.67	2.20	.04*	0.50	1.81	.09
SJ	0.29	0.41	.69	0.24	0.34	.74
Controls, standard	0.20 (.21)			0.18 (.17)		
Controls, suppression	0.20 (.14)			0.11 (.16)		

Local error switch costs are shown in Table 12 (above). Although patients tended to be slower than controls, five of the seven made very few errors in this local task switching manipulation. Although two patients (BQ, ML) showed error rates that were larger than controls on both switch and repeat trials, these between-condition differences were not significant. The remaining patients made very few errors.

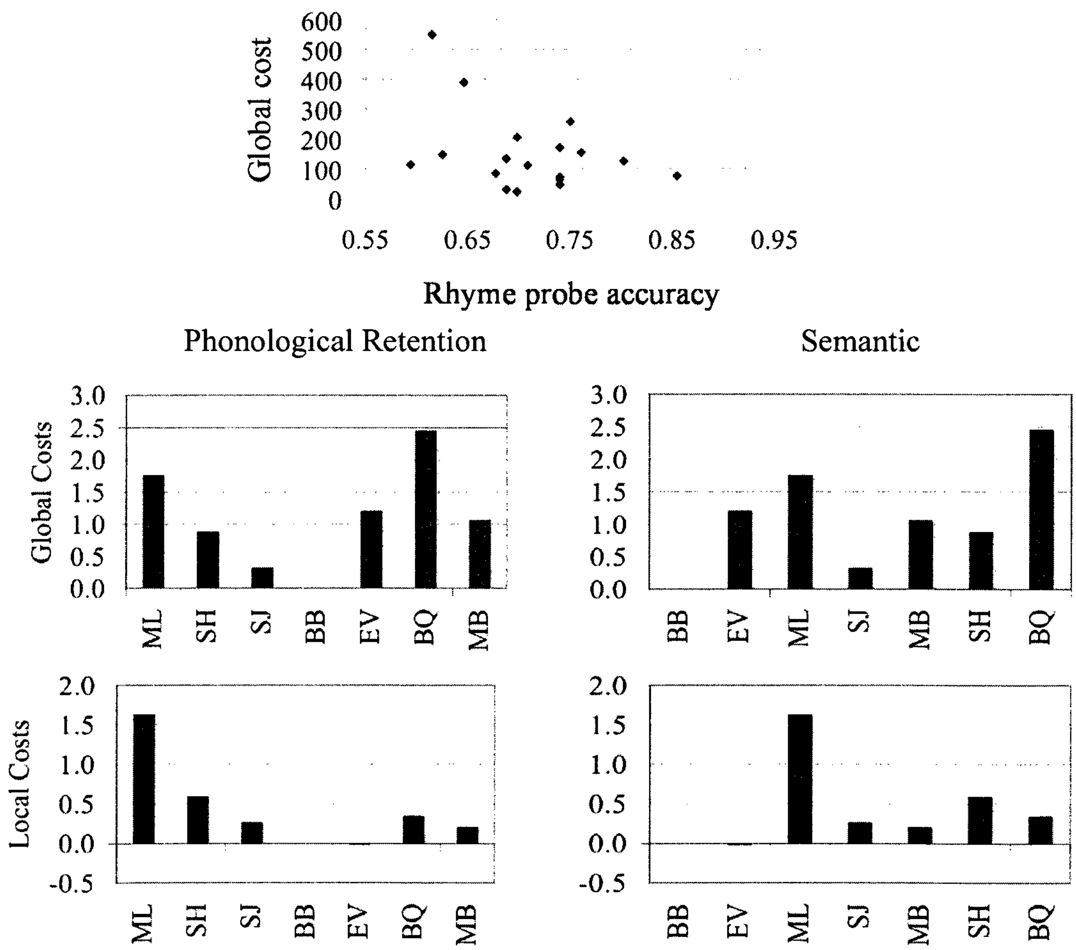
Cross-experiment local switch cost RT comparisons were assessed through the difference between proportional local switch costs (averaged over CSI) in the symbolic cueing condition (Experiment 4) and the full cueing condition (Experiment 2). As can be seen in the bottom Figure 17B (above), only patient ML showed greater cue processing effects than controls in local switch costs. This suggests that, for the most part, that symbolic cueing had little to no effect on patients' local switch costs.

Relationship between switch costs and short-term retention. We again examined the relationship between switch costs and short-term retention. Given that this cueing condition was the only condition affected by disrupted phonological processes (i.e. articulatory suppression), we might expect some relationship between switch costs and short-term retention. Again, relationships were examined in the same way as Experiments 1 and 2.

For controls, the correlation between global switch costs and rhyme probe was not significant, though it was in the predicted direction (r = -.39, p = .11, Figure 18A, top); that is, subjects with larger phonological STM spans tended to show smaller switch costs. More specifically, phonological retention make a significant, independent contribution global switch cost predictions (beta-weight = -.65, p = .03). In contrast, the correlation between global costs and category probe was virtually nonexistent (r = .08, p = .75), with the regression showing an independent contribution opposite of the direction predicted (beta-weight = .45, p = .11). These results suggest that global switch costs in this experiment are related to phonological, but not semantic, short-term retention. As shown in Figure 18B (middle), patient global switch costs again had no obvious relationship with either phonological or semantic retention.

In contrast to global costs, local switch costs correlated with neither rhyme probe ($r = -.25, p = .33$) nor category probe ($r = .25, p = .33$), similar to Experiments 2 and 3. Similarly, neither measure made significant, independent contributions to switch cost prediction (both p's > .15). However, it should be noted that the beta-weight for phonological retention was -.41 ($p = .19$); although not significant, the strength of this weight suggests a relationship might exist (e.g. with more subjects). Patient spans showed no relationship with local costs, as shown in Figure 18C (bottom).

Figure 18. Relationship between switch costs and short-term retention for controls and patients in Experiment 4. 18A (top): correlation between global switch costs and phonological retention for controls. Figure 18B (middle): Patient global switch costs as a function of phonological (left) and semantic (right) retention. Figure 18C (bottom): local switch costs as a function of phonological (left) and semantic (right) retention.



Experiment 4 Discussion

Experiment 4 utilized symbolic cues that had no explicit relationship to their tasks. As such, successful task performance required subjects to either translate symbolic cues on each trial or keep track of the present task by rehearing the sequence of relevant tasks. As a result, the symbolic cueing condition increased the WM demands of this shifting paradigm. We predicted this increase would result in increased switch costs, especially in the suppression condition.

For controls, global switch costs in Experiment 4 were in line with predictions. Global costs significantly decreased as subjects were given more time to prepare for the upcoming trial, consistent with previous research (e.g. Allport et al., 1994; Mayr & Keele, 2000; Meiran, 1996; Rogers & Monsell, 1995). More importantly, as predicted, there was a significant suppression x block interaction, such that AS resulted in increased switch costs, relative to the standard condition. This suppression effect was not found in previous experiments, when explicit word cues were used. Thus, the results from global switch costs support the idea that phonological STM processes are involved in updating, manipulating, and maintaining multiple task sets in WM when exogenous cues cannot otherwise be utilized (e.g. Bryck & Mayr, 2005). Supporting this notion, only global costs in this symbolically cued experiment correlated strongly (though not significantly) with phonological retention; similarly, phonological retention did make a significant, independent contribution to these global switch costs in this same cueing condition.

We did not corroborate the findings of Miyake and colleagues (2004) in local switch costs. As expected, there was a main effect of suppression, as subjects were slower in the suppression condition relative to the standard condition. However, AS did not result in increased local switch costs – there was no significant difference between switch costs in the standard and suppression conditions. While in contrast to the findings of Miyake and colleagues (2004), these findings support the notion that phonological processes are equally involved in both switch and repeat trials (e.g. Bryck & Mayr, 2005; Saeki & Saito, 2004b, 2009). This will be further addressed in the General Discussion.

Looking at the comparison of full vs. symbolic cueing conditions, we again find different effects for the global and local switch costs. In global switch costs, AS results in increased global switch costs in the symbolic cueing condition, but not the full cueing condition. In fact, symbolic cueing only causes increased switch costs in the suppression condition – in the standard condition, symbolic cueing costs are equal to the global switch costs found under full cueing. This lack of symbolic cueing effect most likely result from the task's predictability – in the standard condition, subjects can use phonological processes such as subvocal rehearsal to keep track of the current task set, without needing to process the symbolic cue. This is not the case in the suppression condition, as this inner speech is selectively impaired by suppression (Baddeley et al., 1984). Thus, counter to previous findings (Miyake et al., 2004), less explicit cues may not require a cue translation process if the current task set can be tracked implicitly.

The cross-experiment effects for the full vs. symbolic cueing in local costs indicated an experiment x trial interaction, such that RTs in the full cueing condition were faster than those in the symbolic cueing condition. However, there was no experiment x suppression x trial type interaction, suggesting that AS did not have an effect on switch costs in either experiment. As previously discussed, it may be that phonological processes contribute equally to both switch and repeat trials, with AS slowing both trials types, resulting in no switch cost change. All in all, these cross-experiment results suggest that symbolic cueing affected global switch costs under conditions of AS, but not local switch costs.

In patients, symbolic cueing had detrimental effects on global performance – five of the six patients tested in this experiment showed global switch costs significantly greater than the costs of controls in the standard condition, in both CSIs. Given the variable results in the previous two experiments, these consistent switch cost increases across both CSIs suggest that the increased memory load was particularly difficult for most patients. In fact, patient BB was unable to complete this experiment because of its difficulty. However, fewer patients overall were impaired when patient costs were compared to controls in the AS condition. With these comparisons, only two patients showed exaggerated switch costs across both CSIs. This suggests that patients looked more like controls in the AS condition, suggesting that similar phonological processes maybe disrupted. Additionally, four patients also showed cross-experiment switch cost increases that were greater than controls, giving further support to the notion that memory load affects shifting performance.

In contrast, the patient results in local switch costs are less clear. Only patient ML showed local costs that were significantly greater than controls in both CSIs, with patient SH showing a greater effect in only the 250 CSI. Despite the increased WM load, the remaining patients performed within the range of controls. The contrast in patient performance between global and local costs in the patient data can be taken as evidence supporting the notion that global and local switch costs are, in fact, differentially affected by phonological processes (e.g. Bryck & Mayr, 2005) and measure separate processes (Kray & Lindenberger, 2000; Mayr, 2001; Mayr & Liebscher, 2001).

It should be again noted that patient error rates in this symbolic cueing condition were minimal, and with the exception of patient ML, were within the range of controls. Specifically, we might have expected many errors if patients had difficulty actually executing the task, but their low accuracy suggests this is not the case. Instead, we hypothesize that patients had difficulty keeping track of the task sequence with the lack of explicit cues. Thus, their exaggerated switch costs can be attributed to specific task demands, rather than difficulty in switching tasks more generally.

Only SJ showed switch costs that were within the range of controls, in both global and local costs. This is problematic from a short-term retention point of view, given SJ does not have the largest phonological (or semantic) span among the patients. That is, if her good shifting performance were directly attributable to her STM abilities, we would expect her to have the largest phonological span. However, it is possible that SJ used subvocal rehearsal as a strategy in this symbolically cued condition, similar to controls. In fact, I observed SJ rehearsing the currently relevant task set during testing, supporting the notion that she used rehearsal as a task sequencing mechanism. Given previous research has suggested separate phonological input and output buffers (Martin et al., 1999), it might be the case that SJ has good retention of output phonology. While the rhyme probe task measures phonological retention, it does not require output, and thus taps only the retention of input phonology. If rehearsal of the task sequence requires mainly the output buffer, then SJ's rehearsal may reflect a preserved output buffer.

Therefore, future research should investigate whether input and output phonology differentially contribute to shifting performance.

Also of note is the change in EV's error rates from the partial (Experiment 3) to the full symbolic cueing condition (Experiment 4). In the partial cueing condition, EV made ~20% errors on all trial types (mixed, pure, switch, repeat) – error rates that significantly greater than controls. In contrast, and similar to the full cueing condition of Experiment 2, patient EV made very few errors in the symbolically cued condition. While the exact reason for this difference in performance is unclear, there are a few possibilities. First, it is possible that EV had problems with the retention portion of the partial cueing experiment, such that retaining task-relevant information after cue offset was difficult. This might be expected for patients with STM deficits, as short-term retention is sometimes problematic. However, it is unclear why this cue manipulation only lead to increased errors for EV, but not other patients (e.g. with similar patterns of STM deficits). Alternatively, it is also possible that EV changed strategies in the symbolically cued condition. In the full and partial cueing conditions, she may have considered it unnecessary to keep track of the task sequences on her own – whereas this became necessary in the fully cued condition. Unfortunately, the present data do not distinguish between these (and other) possibilities. The fact that no strong correlations were observed between patients' phonological retention abilities (as measured by the rhyme probe task) and switch costs may result because we measured capacity of the input phonological buffer rather than capacity of the output buffer. This will be a question for future research.

General Discussion

The present research examined the role of WM load in shifting using a predictable, cued task switching paradigm. This research was initially motivated by discrepant findings across different task switching paradigms for one of our patients, which we hypothesized might be due to the differing working memory demands of the tasks. To this end, we initially sought to replicate in older adults previous research with younger adults demonstrating a relationship between phonological short-term memory processes and shifting, by examining the effect of cue explicitness and articulatory suppression on global and local switch costs (e.g. Baddeley et al., 2001; Bryck & Mayr, 2005; Emerson & Miyake, 2003; Miyake et al., 2001; Saeki & Saito, 2009). We hypothesized that patient performance might be like that of controls under articulatory suppression, particularly when cues were not explicit. Lastly, we also sought to determine whether short-term phonological and semantic retention were differentially related to task switching ability, as measured by switch costs.

Global switch costs

We found that phonological processes play a selective role in global shifting, which is considered the ability to update, manipulate, and maintain multiple task sets in WM (Kray & Lindenberger, 2000; Mayr, 2001; Mayr & Liebscher, 2001). Interestingly, in the present study, AS caused exaggerated global switch costs only when task cues were not explicit – that is, in the symbolic cueing condition in Experiment 4. Consistent with our findings, several studies have found differential effects of AS on global switch costs, as a function of cue type (e.g. Baddeley et al., 2001; Bryck & Mayr, 2005; Emerson & Miyake, 2003. More specifically, the results of Experiments 2-4 suggest that successful shifting requires phonological processes a) when cues do not explicitly activate the upcoming task sets (such as with symbol cues) or b) when trials are uncued, and subjects must rely on rehearsal processes to keep track of the currently relevant task (although our results do not speak to uncued trials; e.g. Baddeley et al., 2001). In such conditions requiring endogenous control (Rogers & Monsell, 1995), AS disrupts normal cue processing. More explicitly, Bryck and Mayr (2005) have suggested that phonological processing – or rehearsal/verbalization – effects on global switch costs are "limited to situations in which endogenous control [is] necessary" (p. 614). Thus, global shifting does interact with phonological processes, as a function of task demands – as task demands increase, phonological processes are called upon to maintain previous or update new task sets.

Similar to earlier predictions, if phonological processes become more involved in global shifting as a function of decreasing cue explicitness, we would expect patients with STM deficits to show worse shifting abilities with increased cue difficulty. A first indication of patient performance decrement as a function of WM requirements is seen in the comparison of the results for Experiment 1 vs. Experiment 2. (These experiments were not compared statistically due to methodological differences in the two experiments.) In Experiment 1 (AAAABBBB), only one patient showed global switch costs that were significantly greater than controls in all three CSIs, while two other patients showed greater switch costs in only a single CSI. In contrast, when the switching demands increased through the addition of more switch trials (Experiment 2, AABB), three patients (BB, BQ, EV) showed switch costs greater than controls on both CSIs, with an additional patient (ML) showing greater costs in a single CSI. Thus, simply increasing the number of switch trials within the mixed block produced a decrement in performance. However, one problematic aspect of this cross-experiment comparison is related to practice effects. Many patients (BB, BQ, and EV, included) had previously performed multiple versions of Experiment 1, while participating in previous research in our lab. Therefore, it's also possible that changes in performance from Experiment 1 to Experiment 2 are related to changes in procedure (AAAABBBB vs. AABB). Unfortunately, the present data do not distinguish between these two possibilities.

Moreover, the same three patients (BB, BQ, EV) from Experiment 2, plus one other (MB) showed exaggerated global switch costs in Experiment 3, the partial cueing condition. While BB, BQ, and EV continued to show exaggerated costs, as in Experiment 2, it might be argued that the additional retention requirements in the partial cueing condition caused the fourth patient, MB, to show exaggerated switch costs as well. Lastly, the most difficult cuing condition – the symbolic cueing of Experiment 4 – caused five of the six patients test to show exaggerated switch costs; the seventh patient (BB) was unable to complete the task due to task difficulty. Interestingly, however, patients rarely made errors outside the range of controls, despite exaggerated switch costs. Because patient error rates were not significantly smaller than controls, we suggest that patients were able to execute the shifting task – despite difficulty associated with cue processing demands. As stated by Mecklinger et al. (1999), "brain damage per se did not prevent the adaptation of new task sets or the ability to configure for a new task, but led to suboptimal performance of these control processes" (p. 616). In summary, given that patient performance appears to have decreased as cue processing requirements increased (at least in RTs), the patient results support the notion that global shifting processes are dependent on some sort of STM processing.

Local switch costs

Interestingly, the story for local switch costs is quite different. Local switch costs are hypothesized to represent the processes involved in initiating and executing task set shifts (Kray & Lindenberger, 2000; Mayr, 2001; Mayr & Liebscher, 2001). Previous research has not established a clear role of phonological processes on switch costs, as some studies have found increased switch costs under AS (e.g. Miyake et al., 2004), while others found that AS affects switch and repeat trials equally (e.g. Bryck & Mayr, 2005; Saeki & Saito, 2004b, 2009). Our results were in line with the later findings: across all experiments AS had similar effects on both switch and repeat trials, resulting in no change in local switch costs as a function of suppression. This lack of suppression x trial interaction (in the presence of main effects of suppression) suggests that phonological processes do not make differential contributions to switch and repeat trials. Supporting this, we found no correlation between local switch costs and phonological retention. As suggested by Bryck and Mayr, phonological processes are used to update and maintain the currently relevant task set, a function that needs to be performed on every trial during which there is task set ambiguity. In mixed blocks, both switch and repeat trials may require task sequencing (or maintenance, if multiple repeat trials before a switch, as in Experiment 1). In contrast, task set updating is inconsequential in pure blocks, as subjects know at block onset that they will be performing a single task. Given that AS does not interfere with local task switching processes, Bryck and Mayr have argued that local shifting – that is, actually switching between tasks – may be able to function without phonological processes. Additionally, if local switch cost measures critically involve the retrieval of relevant task sets from long-term memory, as proposed by Mayr & Kliegl (2001b), we would not expect patients with STM deficits to perform poorly, as they have no problems with long-term memory (e.g. Warrington & Shallice, 1969; Romani & Martin, 1999).

Supporting the notion that phonological processes are less involved in the local shifting measures, patient local switch cost results were less consistent than those found with the global switch costs. With global switch costs, there was an increase in the number of patients showing exaggerated switch costs as a function of increased cue processing demands – with the same three patients consistently showing impaired performance across Experiments 2-4 (BB, BQ, EV). With local switch costs, however, the same patients were not necessarily affected across experiments. In Experiment 1, ER showed exaggerated RT costs in all CSIs (however, this patient was unable to return for further testing). In Experiment 2, ML showed exaggerated costs in both CSIs, while EV and MB showed exaggerated costs in a single CSI. In Experiment 3, only BB showed exaggerated costs, and only in a single CSI. In Experiment 4, the most difficult cueing condition in the present experiment, only ML showed exaggerated effects in both CSIs, with SH showing effects in a single CSI. As can be seen, there is little overlap in the individual patients showing exaggerated local switch costs effects, suggesting no specific pattern of shifting impairment. Again, as with global costs, patient errors tended to be well within the range of controls, with a few exceptions. Nonetheless, the hypothesis that task switching (as measured by local switch costs) is not dependent on phonological processes is supported by the patient data – patient local shifting ability was not consistently or detrimentally affected by cue processing requirements.

Interestingly, global and local switch costs showed different CSI effects, as a function of suppression. In Experiment 2, both global and local switch costs significantly decreased across the CSIs in the standard condition, but this decreases was not significant in the AS condition. This same suppression/CSI interaction was found for global (but not local) costs in Experiment 3. In contrast, both global and local switch costs in Experiment 4 decreased as a function of the CSI, in both the standard and AS conditions. One might question the source of the discrepancies in switch cost reductions, across conditions. First, it is possible that this discrepancy is related to power – given these are relatively small effects, it may be the case that we do not have enough subjects to find a significant decrease in all conditions. In fact, switch costs show numerical decreases across CSIs, but these decreases were not significant. Supporting this, Saeki and Saito (2009) did not find different effects of suppression across CSI in young adults.

Alternatively, it is also possible that we would find different suppression/cue preparation effects in older adults (present study), relative to younger adults (Saeki & Saito, 2009). Although no direct comparisons can be made due to methodological differences, it seems possible that there are age differences related to cue processing under suppression, even with explicit word cues. AS may interfere with task set updating for older adults, making them less efficient and therefore slower. If 650 ms were not enough time to complete this updating process, we would expect no switch costs differences from the 250 to 650 ms CSI – which was found. In contrast, 650 ms is enough time to complete the set updating process in standard conditions, as is shown by the switch cost reduction at the 650 ms CSI, as well as previous research (e.g. Rogers & Monsell, 1995). However, it is unclear how this hypothesis relates to the switch cost decreases (across both standard and AS conditions) found in the symbolic cueing conditions. To test this hypothesis, future research would have to include more than two CSIs, in addition to testing both young and older adults, in order to determine whether cue processing is differentially affected by suppression, as a function of age.

Patient ML's previous shifting discrepancy

This research was in part motivated by contradictory performance by patient ML in two task switching tasks. In a Navon figures task, patient ML could successfully respond to the targets when they were presented in pure blocks, but not mixed blocks. Each trial in the mixed block required cue interpretation – task set was not indicated by an explicit cue, but by a more implicit color cue. In contrast, patient ML performed normally in a predictable cued shifting task, similar to Experiment 1. The present studies were a test of the hypothesis that ML's performance differences were critically related differences in the task demands between the two shifting tasks, as ML shows reduced semantic and phonological STM capacities.

The present experiments speak to this issue. First, the fact that phonological processes may be involved in both switch and repeat trials, when exogenous information is minimal, suggests that high load conditions may be particularly difficult. Specifically, examination of patient switch costs, as was done in Experiments 2-4, masks the fact that patients were much slower than controls in both switch and repeat trials, despite showing switch costs similar in magnitude to controls. In fact, ML show exaggerated local switch costs in Experiment 4, which is the most similar to the Navon figures task in terms of cue processing demands. And, this symbolic cueing condition is still easier than the Navon figures task, as task sets can be tracked and updated using phonological processes. These findings support the notion that ML's difficulty with the mixed block of the Navon figures task might very well have been related to differences in the memory demands between the two tasks, reconciling his performance across the two tasks.

Shifting and short-term retention

Lastly, we also sought to determine whether short-term phonological and semantic retention were differentially related to task switching ability, as measured by switch costs. Given that previous results have indicated a role for inner speech (i.e. phonological STM processes) in global shifting conditions requiring self-sequencing, we expected to find a relationship between phonological retention and switching in conditions requiring endogenous control. In contrast, the relationship between semantic retention and shifting performance was, for the first time to our knowledge, under investigation. In line with previous findings, indicating a detrimental effect of AS on switch costs when endogenous processing requirements are high, we found a correlation between global switch costs and phonological retention in only the symbolic cueing experiment. On the contrary, we found no relationship between shifting performance and semantic retention. While these findings need to be expanded to a larger control sample for verification, they suggest that phonological but not semantic STM is critically involved in task switching, as least when endogenous processing requirements are high. As discussed in the next section, this findings has implications for interpretations of executive impairments in patient populations demonstrating STM deficits.

Implications for the relating STM deficits and executive impairments

As discussed in the introduction, Hoffman and colleagues (2009) have recently suggested that semantic STM deficits result from deficits to a domain-general semantic control system. However, Hoffman and colleagues have done little to specify whether these semantic STM deficits result from deficits to specific executive functions, as proposed by Hamilton and Martin (2005, 2007). Relevant to this issue, global executive deficits as the source of semantic STM deficits would predict that the patients with the most impaired semantic retention should show the most exaggerated switch costs, across both global and local measures, as are both costs are presumed to measure aspects of executive control. In fact, while it is the case that two of the patients with the lowest semantic spans (BB, EV) showed exaggerated global switch costs across Experiments 2-4, patient BQ showed these same exaggerated costs, despite having the highest semantic span of the patients tested. Additionally, any potential relationship between semantic STM and global executive deficits does not hold up when looking at local switch costs: patients with the lowest semantic STM spans were not the only patients showing impaired effects, suggesting no specific relationship between semantic STM deficits and two measures of shifting, an executive function.

Also in contrast to the suggestions of Hoffman and colleagues (2009), Allen, R. Martin, and N. Martin (in preparation) have provided evidence suggesting that the relationship between executive function and STM deficits might be better interpreted in the other direction, with deficits in short-term phonological retention causing deficits on executive function tasks that have a verbal component. Results from the present experimental paradigm support this notion: as found in controls, increased cue processing requirements result in increased need for phonological processes in global shifting measures. Additionally, these increases in phonological requirements also lead to exaggerated global switch costs in patients. These findings therefore support that notion that at least some portion of the deficits patients show in executive function tasks may be related to memory-related task demands. These findings have implications for any neuropsychological study drawing inferences about executive deficits.

Limitations and future directions

Of course, this study is not without it's limitations. First, the relationship between shifting and phonological retention in control subjects should be interpreted with caution. Given we have just under 20 subjects, we have limited power to detect a relationship and run regression analyses. The fact that we found a relationship in line with previous research, as well as a significant contribution of phonological retention to shifting, is promising. However, this finding needs to be validated in a larger sample of subjects. Similarly, the lack of relationship between patient performance and measures of short-term retention should also be interpreted with caution. Given previous research, we had no reason to expect a relationship between shifting ability and semantic retention. However, we might have expected to find a relationship with phonological retention, as with the controls. The lack of relationship within the patient data is likely caused by two factors. First, we had only 6-7 patients in each experiment. This small sample size restricts statistical methods that can be used to investigate relationships between two measures. Similarly, our patients also showed a very limited span ranges (phonological: 1.75-5; semantic: 1.5-4), which also restricts our ability to detect a relationship. Perhaps, with a larger group of patients, we would be able to detect to do so. However, it is of note that a study with a larger group of patients (N = 19; Allen, R. Martin & N. Martin, 2009) also failed to find a relationship between short-term retention and global switch costs in conditions similar to Experiment 2 (full cueing).

Lastly, although we suggested a relationship between global shifting and phonological STM, the exact nature of this relationship still needs to be specified. As discussed in the discussion of Experiment 4, output phonology (Martin et al., 1999) might be critically involved in task switching. In the present study, we measured phonological retention using the rhyme probe task that measures phonological retention, but mainly on the input side (given this is a recognition task). In controls, input and output measures are likely highly correlated with each other. However, as Martin et al. (1999) have shown, this is not the case for patients, as patients can have selective deficits to either input or output. The suggestion that both input and output should be assessed comes from patient SJ's normal performance in the symbolic cueing condition, relative to the other patients with similar STM deficits. These results suggest that measurements of input phonological storage may not tell the entire story. Additionally, in theory, it is phonological rehearsal, or the output side, that is being disrupted by articulatory suppression in controls. As such, future research should investigate phonological input *and* output, to see whether these measures differentially contribute to shifting performance.

Summary and conclusions

In summary, the present study investigated the relationship between shifting and cue processing to determine whether global and local switch costs changed as a function of cue processing. Supporting previous research, the present results found different effects for global and local switch costs, supporting the notion that a) phonological processes are differentially involved in these two measures of shifting and b) these shifting measures are actually assessing different cognitive processes (Kray & Lindenberger, 2000; Mayr, 2001; Mayr & Liebscher, 2001). These results have implications for models of shifting, as well as models of STM deficits that propose global executive deficits as the source of semantic STM deficits.

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